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THE DEPTH-ZONES IN ORE DEPOSITION.[1]

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INTRODUCTION.

Great Vertical Range Proved.—The depths to which ores persist and the physical and chemical differences which they display at various levels below the surface command perennial interest. Mines everywhere are deepening, and generally at rates never before equalled. Nearly a score of mines on four continents have now reached vertical depths of from 5,000 to nearly 8,000 feet. This opens both new problems of mine operation and new opportunities for geological observation. As it has been my privilege to examine all these very deep mines within the last four years, I take this occasion to present some generalized impressions on the subject of ore deposition in relation to depth. Great practical importance obviously attaches to this question; but of that no general discussion will now be attempted. Attention will here be confined to certain considerations of distinctly geological significance.

Since an ore body varies in richness or character from point to point chiefly because of conditions controlling its deposition, discussion of the effects of depth cannot be kept independent of hypotheses of origin.

For those few metals, notably aluminum, iron, and manganese, so plentiful in the usual rocks that a relatively small multiplication of content would afford material of commercial tenor, it has been amply demonstrated that this comparatively easy task of concentration can be accomplished at especially favorable places by so simple and familiar a process as weathering or by so feeble but sustained an instrumentality as the sub-vadose circulation. For this restricted but highly important family of deposits, the time-honored theory of genesis by meteoric waters stands secure. But

such ores, when unaffected by later structural relocations, possess a simple mineralogy and a relatively monotonous character in general accord with what the theory of their superficial origin would imply. Therefore, such deposits ordinarily add but little to our understanding of the intensely interesting processes that go on at depth, and for that reason will not be considered here.

For most types of ores, however, considerations had led, by the early years of the present century, to firm establishment of a deep-seated magmatic source. This opened the conception of deposition of ores at depths much greater than had previously been seriously entertained. Nevertheless the evidences supporting magmatic derivation were, for the most part, merely *permissive* of persistence to great depth in given cases; there was little of *compulsion* about them. Metals might be *derived* from abysmal sources, the requisite heat, the mobile medium of transfer and the necessary transporting power might likewise there be supplied—still, the metals might be *deposited* only at depths far shallower than the source. Notwithstanding suggestive contributions by Vogt, DeLaunay and others, there remained a gap in both the evidence and the argument for the actual formation of ores at great depth.

Toward the filling of this gap, nothing has contributed so much, whether in the way of clarifying and extending earlier ideas or of adding entirely new ones, as the epoch-making paper of 1906 by Lindgren, showing the control of physical conditions on ore deposition. It was my great fortune to serve as Professor Lindgren's assistant during the years when many of his ideas on this subject were taking form and being tested against actual occurrences in many regions. To that inspiring association must be ascribed the initiation of interests which find in my present remarks all too unworthy a reflection of the stimulus.

This conception of physical control (really, physico-chemical control) applied to his enormously rich and intensive field experience with ore deposits enabled Lindgren to achieve that long-sought accomplishment, a classification of mineral deposits based consistently on origin. By this doctrine of physical control and its later elaborations, Lindgren also showed how, particularly for

that vast family of hydrothermal deposits, it is possible to envisage the entire vertical range of vein deposition, and to set up a threefold grouping: hypothermal or deepest, mesothermal or intermediate, and finally epithermal or shallow, the last-named merging at its upper limit into the hot-spring deposits at the very surface. Conversely, from the mineralogical and textural character of ore and adjoining alteration, a given deposit can be assigned to a definite place in this vertical range, inferences drawn as to amount of erosion it has suffered since formation, and predictions made as to its character still deeper. This was the most clear-cut recognition and exposition that had yet appeared regarding systematic and progressive change in character of deposits of common source. Although Lingren did not use the term, he plainly demonstrated the importance and the necessity of *mineral zoning,* especially in the vertical sense, as a consequence of the inevitably changing physical conditions attending deposition. The value of these conceptions has been widely recognized.

Closely related in many ways to this theory of physical control is the zonal theory, definitely so-called. Likewise glimpsed by various earlier investigators, this theory first found generalized expression by Spurr, and has received later elaborations by De Launay, Sales, B. S. Butler, W. H. Emmons, Rastall, Berg, and others, especially with respect to horizontal variations and as regards definite positional relation of the deposits to the parent intrusive body. This conception, also, has demonstrated its value by aiding in the interpretation of many occurrences.

More recently Niggli, who has approached the question rather from the strictly physico-chemical side than that of field observation, has presented a classification of the ores of magmatic derivation, full of suggestive and enlightening viewpoints and definitely in accord as to many major implications with the theories of physical control and of zonal arrangement. Schneiderhöhn, Berg and various other Continental geologists have indicated substantial accord with Niggli's conceptions.

While these three lines of approach differ somewhat among themselves and in certain respects appear even incompatible with one another, they are in complete agreement in proving a great

vertical range within which ore deposition is actually accomplished. What had been *permissible* as to depth has now become *compulsory*.

Scope of Present Considerations.—This firm theoretical background of ore occurrence and the actual evidences now afforded by the deep mines jointly make it possible to consider the effects of depth on ore deposition with somewhat more of confidence and definiteness than has perhaps been justifiable hitherto. It seems permissible, also, to take inventory of the existing classifications of those ore deposits in which the depth factor is of prime importance, and to suggest for consideration certain modifications that have as their aim the bringing of theory into better accord with the facts now known.

No attempt will be made to consider here the various relationships of depth that are independent of initial deposition, such as later structural deformation, aggradation, and superficial impoverishment or enrichment; erosion enters this consideration only as it enables us to see what once was deep and thus to improve the ratio of fact to speculation regarding conditions at depth.

Two factors affecting initial deposition, namely, rock character and structural conditions, are in large measure independent of depth. They therefore influence the broad principles and tendencies of mineral deposition rather in a locally modifying than in a broadly controlling manner. For the individual occurrence or locality, they may be of the greatest importance; but they will be considered here only as they affect ore deposition in a general way.

Attention will be further restricted to such types of deposits as potentially possess a great initial range of vertical extent. It is immediately evident that the ores which have the best chance of deposition through a great vertical range and are thus most likely to disclose inherent influences directly due to depth are those which have long been classed as hydrothermal. The remainder of my remarks will, therefore, be confined to ores that may be regarded as belonging to the hydrothermal lineage, the limits of which I suggest expanding substantially.

Emphasis is put on the intimate but changing relationships that permeate the entire hydrothermal group and that serve to join all its variations into one coördinated family. In particular, the factor of depth is kept to the forefront, both because of its intimate bearing on conditions of ore genesis and because, of all the influences that affected ore precipitation at the time the deposits were formed, depth is the one that most tangibly survives for observational consideration at the present day. Moreover, since the vertical ranges of the hydrothermal zones appear to have been under-estimated, the quantitative aspects of depth are given prominence.

The principal deviations herein from Lindgren's treatment of the hydrothermal deposits consist, first, in the proposed inclusion of certain types of deposits that have not hitherto been regarded by all as embraced within the hydrothermal family, and second, in the suggestion that to the three hydrothermal zones of Lindgren two more be added by mild rearrangement of the former boundary lines.

Doubtless many others have duplicated my frequent and disillusioning experience in finding that a given occurrence, when seen face to face, differs in surprising degree from my previous mental picture of it gained from descriptions by others. That the personal equation should enter profoundly into all geological conclusions that rest upon the literature is inevitable. But it is none the less unfortunate; for there are enough grave imponderables inherent in so complex a subject as ore genesis without adding enormous human variables. Therefore, with the hope, not of eliminating the personal factor, but of holding it herein as nearly constant as possible, I am choosing examples preferably from occurrences which I have visited; other examples cited in these pages are distinguished by an asterisk, to serve notice that they necessarily stand on a different basis or denominator of interpretation.

THE HYDROTHERMAL DEPTH-ZONES.

Foundations of the Argument.

Basis of Subdivision.—The major conceptions underlying Lindgren's classification of the hydrothermal lineage into a number of subgroups appear fundamentally sound and enduring. If I venture to suggest what seem to me to be desirable modifications of detail, this only serves as confirmation of my respect for the basic idea. No attempt is made to present a complete and self-sufficient classification of the hydrothermal deposits. I shall merely here and there attach certain comments to the general framework established by Lindgren.

Adherence to the general Lindgren classification in no wise excludes, as I see it, acceptance of the zonal theory in its present form. But it appears helpful and logically sound to recognize primarily a few inclusive groups based on the broadest controlling conditions of deposition and then to subdivide these into as many individual types as may be thought desirable. This Lindgren has successfully done, as illustrated, for example, by his sub-sections "Tin Deposits," "Gold Deposits," etc., under the hypothermal group. In this way is produced what seems to me a more truly genetic and a more practically elastic classification than that toward which the zonal supporters seem to be tending in piling on top of one another something like a score of types distinguished chiefly by metal content. The number of such types is almost certain to grow, and the instances of recurrence of the same metal at different elevations to multiply, as our information increases, thus causing this cumulative straight-line method of classification to become more and more unwieldy and empirical. Niggli's recent classification stands somewhat between these other two, but decidedly closer to the zonal scheme.[2]

[2] Since this paper was presented, Schneiderhöhn has brought out a modified classification (Zeit. prakt. Geol., 40, Heft 11, pp.1–4, 1932) which follows the general views of the present-day German school; but in the application of his classification to German ore occurrences (Metallwirtschaft, 11, Heft 46, p. 619, 1932) he shows a degree of approach to Lindgren's idea of physical control by recognizing high-, intermediate- and low-temperature subdivisions for a part of the hydrothermal series.

Essential Postulates.—Certain assumptions or postulates are made necessary by the limitations of our positive knowledge regarding conditions deep in the crust. My principal assumptions required for present purposes apply to the physico-chemical character of the hydrothermal solutions and are listed below without present attempt at argument in their support. These postulates are assumed to apply in the *general* case; they may be to some degree discounted or even upset in certain local instances.

Source and Composition.—The hydrothermal fluids are evolved from the magma body before and during its crystallization. When crystallization is completed, their evolution ceases. They acquired their dominant characteristics of temperature, pressure and composition from the magma source itself, and they tend to lose these characteristics progressively as they move into alien surroundings. The water and other volatiles contained in these solutions are of magmatic derivation equally with the metals and other uncommon non-volatile components. The proportion of volatiles collectively to be regarded as the solvent generally dominates greatly over the proportion of constituents capable of deposition as mineral material. From among the somewhat conflicting opinions of physico-chemical authorities, preference is given, primarily on geological grounds, to the assumption that the hydrothermal solution is predominantly liquid; nevertheless transformation into the gaseous state is everywhere potential through faster loss of pressure than of heat, and may, at local points, be in some degree realized. Save possibly and occasionally close to the surface, the solutions are of alkaline character and in a state of true molecular dispersion. When the hydrothermal solutions pass into that very shallow region where the free groundwater exists in any important quantity, these ascending solutions, by virtue of their great volume and the pressure they transmit, flush out and displace the groundwater from the localized channelways of their ascent and hold it at a distance until their work along these main channelways is virtually done.

Pressure.—The solutions are under great pressure at the magma source. They move because they find opportunity to escape from that pressure, and the net eventual direction of

escape is upward to the surface or to the highly fractured rocks near the surface. The system, while active, is open and hydrodynamic rather than hydrostatic, and great pressure differences may exist in it simultaneously at different places; in general, the pressure declines from source to outlet, ordinarily at an accelerating rate upward. Because of the great excess of non-depositable solvent which must be disposed of for each unit of solid material deposited at any particular place, a single filling of a given open space by hydrothermal solution is entirely inadequate to fill that space with minerals; repeated refillings are necessary. Corresponding requirement applies to replacement. This involves maintained circulation and puts as great necessity on outlet as on source. When crystallization in the magma chamber ceases, driving pressure on the solution ceases and flow stops.

Temperature.—Temperature of the solutions ordinarily declines from source to outlet. Reactions of a net exothermic character in which the solutions participate are more than offset by loss of heat through the walls of the channelway, which are assumed to be everywhere initially colder than the solutions themselves. Therefore, although any given portion of the solution is constantly losing heat as it ascends, the channelway wall at any given level and the deposit there formed are generally and for the most part subjected to rising temperature through continued flow of solution until the crest of the mineralizing episode is reached. Thereafter, there is rapid decline in evolution of solution at the source, expelling pressure falls, flow dwindles, and relatively little takes place along the channelway save the cooling down of the deposit and its walls to the temperature normal for that depth and that region.

Intensity Factor.—The interaction or integration of the three preceding qualities of the hydrothermal solutions, *i.e.*, temperature, pressure and composition, constitutes a composite quality that may be designated the physico-chemical intensity of the solutions. The resultant effect of this degree of intensity of the solutions on the local environment of rock character, structural detail and geothermal value at any given point along the solution path-

way may be termed the "intensity factor" of ore genesis at that point.

In a region where rock character, thermal gradient and all structural features are ideally homogeneous and constant, the physico-chemical intensity of the solutions and the intensity factor will have essentially parallel values or at least intimately related values through the entire range of hydrothermal deposition. The change in character which the solutions would experience by ascent through that range in such an ideal region would be orderly and progressive, and might by typified by a line of simple and smooth curvature—the "depth-intensity" curve. Various considerations indicate that this change in intensity of the solutions and in the intensity factor would, in such an ideal region, take place at a steadily (though perhaps slowly) accelerating rate upward from source to outlet; the depth-intensity curve would thus show increasing curvature from bottom to top of the hydrothermal range.

Variations in rock character or structure, in nature of the channelway, or in the geothermal gradient—that is, departures from the ideal just discussed—would manifestly affect the slope and the smoothness of the depth-intensity curve. But these local deviations would not suffice to rob the curve of its general character; it would still show a dominant acceleration of curvature upward, representing a cumulatively declining intensity factor.

The character of ore deposited at any depth is determined by the physico-chemical intensity of the solution at that depth and by the local environment. The *character* of ore that is pertinent from the standpoint of genetic process and significance is not necessarily concerned with economic richness or quantity, but rather it is the composite of those chemical, mineralogical, and textural qualities which we recognize as indicative of the conditions of its formation. In order to distinguish this particular kind of character from that more general character of customary parlance, the former may be called intensity-character. A hypothermal ore would thus be a relatively high-intensity type, and an epithermal ore would normally be of lower intensity-character.

Evaluation of Depth Factor.—Lindgren has presented estimates of the depths of formation of each of his three hydrothermal sub-groups. It seems extremely helpful, for both practical and philosophical purposes, to attempt such quantitative expression of the depth factor, even though it be recognized that in our present state of understanding only rough and perhaps highly imperfect approximations can be expected. Lindgren's method of arrival at arithmetical rather than merely relative specification of depths appears to rest primarily on the amount of erosion suffered by the given locality since the deposits were formed; and this, in turn, is ordinarily derived from a theoretical restoration of the stratigraphic column of that locality. Ideas reached by this means he has subjected to whatever check may be gained from such miscellaneous considerations as the depth to which voids can persist, strength of the body of rock overlying any given point at depth, the effects of pressure due to the rock column and to the hydrostatic column at given depths, the critical pressure of water, losses due to friction of the moving solutions, and indications of vertical persistence of given deposits.

Apparently recognizing the dangers in trying to translate into definite values any or all of these factors (most of them pretty speculative in themselves), and with his characteristic conservatism, Lindgren has reached estimates of formation below the then-existing surface which appear to range about as follows, stated in feet:

Epithermal	0 to 4,000 (?)
Mesothermal	3–4,000 to possibly more than 12,000
Hypothermal	3–4,000 to what he evidently regards as a very speculative extreme of 33,000

One of the checks used by Lindgren in estimating these ranges of depth impresses me as affording a more direct and probably a more reliable answer than can ordinarily be had from any or all the other means combined: namely, the actual indications as to vertical persistence afforded by the deposits themselves. It seems possible, moreover, to make effective use of this kind of information over a substantially greater vertical range than that actually revealed by any mine-working or mountain-side exposure.

This may be achieved by making from the disclosed facts extrapolations that seem decidedly conservative and dependable, as geological extrapolations go. The manner of this application may be indicated in the following hypothetical example.

Let it be assumed that at the present erosion surface there is found a body of ore having such characteristics as to indicate that it belongs beyond all question in, say, the hypothermal zone. Let it be further assumed, for the sake of simplification, that the geothermal gradient, the country rock and the structural environment of this ore deposit remain constant for as great a depth as we may wish to imagine; also that the attitude of the deposit in space has not been disturbed since formation.

If the physical-control theory has any validity, it must mean that the nature of this ore which causes us to classify it as hypothermal is a consequence of the physico-chemical conditions that prevailed at this place when this ore was formed. Somewhere above, in the region now eroded away, conditions of a lower order of physico-chemical intensity must have prevailed and have produced ore differing therefore from that with which we are here dealing. Likewise, at some greater depth, ore there present ought to begin to show effects of more intense conditions attending its deposition. We assume that in due course mining opens our discovered deposit to the 1,000-foot level where it is still continuing downward. And we find that in this 1,000-foot vertical span, although the nature of the ore varies somewhat from place to place, there is no discoverable progressive or systematic change with depth; so that representative samples of adequate size from the upper, the middle and the lower parts of this span are found to be essentially identical. Stated otherwise, the rate of change in intensity character of the ore with depth is undiscoverably small. As will be seen, the *rate of change with depth* is the core of this entire conception.

The problem now is to extrapolate sanely from this known 1,000-foot portion of the deposit. Our theory demands that in a 1,000-foot span there must be *some* change in intensity character. Therefore, although we have been unable actually to detect any change, we will assume that there is an extremely slight

decline in intensity character from bottom to top of this exposed span. It is clear that we are dealing with ore which belongs well down on the depth-intensity curve, where its curvature is very small; this tallies with our initial diagnosis of the ore as hypothermal. Extrapolation then consists in extending the ideal depth-intensity curve upward and downward from the known or base-line portion. Our conception of the shape of this curve makes it evident that extrapolation from the position of the known base-line can be carried along the curve for a very considerable distance above and below the known span without leading to ore of *substantially* different intensity character from that exposed.

It must obviously be left for judgment to decide how far such extrapolation may be carried before encountering ore of a character that is obviously different from that in the exposed span. My own experience with deeply mined ores and the reflections therefrom lead me to conclude that for any considerable vertical span of ore in which no systematic change in intensity character can be detected, one is safe in assuming that ore of the same order of character extends for an equal span above and an equal span below that known. In the example we have been using, then, it could be predicted that ore of virtually the same intensity character as that exposed could be counted on through three times the developed span, or 3,000 feet.

But had the actual vertical development of 1,000 feet disclosed a pronounced difference in character of ore as between top and bottom of that span—that is to say, a relatively rapid rate of change in character with depth—then it is obvious that extrapolation above and below would have to be done with greater caution and restraint, more exacting judgment, and keener understanding of the various ways and degrees by which ores change with depth. Under such circumstances one might predict, for example, that 1,000 feet deeper the hypothetical ore deposit would still belong in the same zone as that of the exposed and known portion, but 1,000 feet higher the ore might possibly belong in the next shallower zone. (As a matter of fact, it may be added that any ore which would show a pronounced change in intensity-

character in 1,000 feet of depth would either belong in some zone higher than the hypothermal, or else would owe its change to other cause than mere depth difference.)

On the other hand, if mine development showed the ore to possess virtually constant intensity character over an exposed vertical span, not of 1,000 feet as first assumed, but of 5,000 feet or even 7,500 feet (as is actually known in certain deposits), then the slowness of the rate of change with depth is still further emphasized and confirmed, and extrapolation through equal spans above and below is all the more secure.

Obviously, the more rapid the rate of change, the thinner the vertical range of any given character of ore; also the higher on the depth-intensity curve does that ore belong.

It is to be clearly understood that this method of extrapolation is intended for estimating the vertical range of the *zones,* or the vertical range of the locus physico-chemically favorable for the deposition of ore of a given intensity-character; it is not intended for predicting the distance through which commercial ore may persist nor the vertical dimension of individual ore shoots. (In this connection, it may be noted that, for the average case, the lateral dimensions of any of the zones are likely to be substantially less than the vertical dimension, because of the dominating *upward* direction of movement of solution, solutes and heat, and the more rapid loss of pressure upward than horizontally. Thus, in an ideal example, the successive zones will not be concentric hemispherical shells, as is so often implied, but rather interfitting conical sheaths.)

It need hardly be added that the validity of all such extrapolations depends on the degree to which the environment of the exposed ore, in the way of rock character, structural conditions, and thermal gradient may be counted upon to persist essentially unchanged through the range covered by the extrapolation. If change in environment must be entertained, extrapolation becomes less dependable. Validity of the extrapolation depends also on the thoroughness and sagacity with which the intensity-character of the known ore is appraised, as exposed at various levels, and on the success with which characters truly dependent

on the depth factor are distinguished from those due to wholly local influences.

It is evident that this method of evaluating the depth factor depends almost exclusively on what the ore itself discloses. There is no reason why conclusions so reached should not be checked by the various other methods already mentioned. My own experience, however, has led me to the conclusion that the method of extrapolation from the ore itself is, for the general case, safer and more practicable than any other. But in those relatively few regions which have suffered so little erosion since ore deposition that the then-existing and the present surfaces can be correlated by definite physiographic links—and short, sure links, at that—ore depths may perhaps be estimated over relatively shallow ranges more precisely in that way than by the rate of change in ore character.

The very important effect of depth of the magma-source on the rate of vertical change in character of ore, and thus on the vertical ranges of the several zones, is considered on page 532.

The Hypothermal Zone.[3]

General Characteristics.—The deeper limit of the hypothermal zone, and thus the beginning of the hydrothermal lineage, is marked by the first or deepest appearance of those deposits which contain too little of the pyrogenic minerals to be classed as either orthotectic or pneumotectic deposits. Whether underlying pegmatites and other pneumotectic products, where present at all, are separated from the hypothermal ores by gap or by transition probably depends in each given case on the particular conditions there governing.

The mineralogy characteristic of the hypothermal zone has been effectively set forth by Lindgren. A few words, however, may well be devoted to the quartz, both here and in appropriate place for each of the other zones. Because quartz, with the possible exception of pyrite, is the most abundant of all the hydro-

[3] It is unfortunate that the division-name *hypothermal* is so similar in appearance and sound to the group-name *hydrothermal*. One could wish that for this deepest subdivision Lindgren had initially adopted *katathermal*, as Niggli has done.

thermal minerals, and the mineral most abundant (if cryptocrystalline varieties be included) in each of the zones, it is evident that if the quartz should disclose any features indicative of the conditions of its formation, the abundance and ubiquitous presence of the mineral would make those features highly valuable for diagnosing the intensity character of the containing deposit. Fortunately, quartz does often show rather delicate response to the conditions of its formation; this is revealed both in grain-size and in transparency. In the hypothermal deposits the quartz ranges from perfectly clear, colorless and glassy through various sub-vitreous dark colors to the dull white of typical "bull quartz." The size of the individual grains tends to be large wherever the surroundings permit, so that coarse-grained aggregates are the rule. An extreme instance is afforded by the Messina copper deposit, in the northern Transvaal, where, in the midst of a solid ore that combines strong hypothermal characteristics with some puzzling anomalies, fairly well-formed prisms of sub-vitreous quartz attain maximum dimensions of 10 inches in width and several feet in length. As a rule, the greater the intensity-factor of the ore, the coarser and more vitreous is the quartz likely to be; but this criterion can of course be used only in conjunction with others, and final diagnosis must be based on the net resultant indication of all the available criteria.

It is desirable to emphasize that there are probably no sharp breaks in mineralogy or other diagnostic characters from zone to zone; but that on the contrary, continuous serial relationships persist throughout the hydrothermal group. And the same *kind* of progressive changes which, seen in the large way, justify the distinction between hypothermal, mesothermal, etc., exists also on a smaller scale within each of these subdivisions. Thus it often becomes evident that certain individual deposits undoubtedly belong deeper in, say, the hypothermal zone, than do certain other occurrences which are no less definitely hypothermal. This ability to recognize vertical changes not only from zone to zone but also within a given zone unquestionably improves our basis for estimation of the depth factor.

A distinctive feature of this zone is the extremely irregular shape of many of the deposits which must nevertheless be called veins. These bodies—swelling, pinching, splitting and writhing —have, as a rule, been initially deposited thus, and have plainly been in large measure localized by fractures or places of weakness that already possessed approximately analogous contortions. The *irregularity* of such actual or potential openings is unquestionably in the main a consequence of depth. On the other hand, even with allowance for some enlargement by marginal replacement, the *size* of such openings *as preëxisting voids* is entirely incompatible with the rock pressure inevitable at these great depths. It is therefore necessary to conclude that the walls of the openings, originally tightly pressed together and mutually self-supporting, have been spread to something like present widths during the mineralizing activity. Since the " force of crystallization " is entirely incompetent for so extreme a task, reliance must be placed here, just as for the simpler, straighter veins of shallow levels, on intrusive pressure transmitted to the walls by the very solutions from which the deposited mineral was derived. But of course this intrusive mechanism does not demand, as Spurr assumed, that the fluids involved were either concentrated or viscous.

The absence or unimportance of druses in these deep-seated deposits comports with the following conditions: the impossibility of maintaining unsupported openings of any appreciable size at such great depths, the driving pressures that cause the solutions to flow, the more concentrated character of the hydrothermal fluids at these depths than higher up, and the greater efficacy of molecular diffusion as well as the tendency toward lowered viscosity in the solutions at the relatively high temperatures here prevailing. The deepest veins are usually " frozen " to their walls, without partings or selvedge.

As contrasted with the abundance of definitely localized deposits of the vein type, great replacement deposits are less abundant among the deeper hypothermal ores than they are in the upper hypothermal and in the mesothermal ranges. Where they do occur, these replacements tend to be highly selective, often devouring certain favorably conditioned rock masses completely and leaving adjacent rocks but little affected. The usual gradational

evidences of metasomatism may, therefore, be less obvious than in replacement bodies formed at shallower depth; the nature of the marginal rock alteration, mentioned below, likewise tends to disguise replacement effects in the deepest hypothermal deposits. These replacement deposits also demonstrate the great magnitude of the impregnation pressures, as well, probably, as the high efficiency of true molecular diffusion at these elevated temperatures, in order that deposits with dimensions of hundreds and thousands of feet may be formed by selective replacement of massive rock.

The nature of the alteration in the immediate walls of the hypothermal deposits, while influenced by the composition of the rock itself, is further dependent on the physico-chemical intensity of the solutions and thus upon depth. In the higher parts of the hypothermal zone, rock alteration marginal to the deposits is clearly a superimposed process, yielding a product ordinarily distinguishable without great difficulty from the unaltered country rock through differences in color and grain-size as well as by more or less complete destruction or modification of the texture of the initial rock. In this respect, transition toward the overlying mesothermal zone is forecast. But deep in the hypothermal zone the marginal alteration may often be crisp, sparkling, macrocrystalline aggregates of darker shades of color, quite unlike the lusterless, fine-grained or earthy, and often faded alteration margins characteristic of the shallower zones. Where, as is so often true, the country rock of these deepest hypothermal ores is a crystalline schist, the alteration bordering the deposit proper may itself closely resemble, in general mineralogy and texture, an "unaltered" schist—a resemblance especially marked where, as is so common at depth, the plane of the deposit has been in large measure determined by the regional foliation.

Fahlbands Included Here.—The so-called fahlbands have been much bandied about in geological literature without finding a very satisfactory or recognized resting-place in any systematic scheme of ore classification. By some, ores of the fahlband type have been ascribed to a process of selective segregation from surrounding formations during regional metamorphism; others regard them as preëxisting deposits of syngenetic or other origins re-

worked to present condition by deep-seated metamorphism; and by still others they are described rather cryptically as sulphide impregnations.

From the considerations given shortly above regarding the characteristics of the hypothermal replacements and the ease of overlooking rock alteration attending deep-seated ore deposits, it would seem reasonable to assume that most of the so-called fahlbands, as well as many more massive pyritic bodies in schistose rocks, are virgin hypothermal introductions by selective replacement. Mineralogy, texture, structure and general environment seem compatible with this view that these are merely certain deep-seated phases of the hydrothermal family.

Contact-Metamorphic Type.—There seems at present no certain general way of distinguishing between those deposits formed by volatile-rich solutions that left the magma source respectively prior to, and in consequence of, wholesale orthotectic crystallization. Perhaps it is partly on this account that the contact-metamorphic ores appear to occupy a somewhat unconnected and anomalous position in the usual scheme of classification. Possibly in order to avoid this difficulty, Niggli places these contact deposits in his " pegmatitic-pneumatolytic " or pneumotectic class. But the mineralogical and compositional relations do not seem to support such grouping. On the other hand, the contact-metamorphic deposits have many significant minerals and certain other features in common with the normal hypothermal deposits, as Lindgren has noted. I merely go still further by believing that the contact-metamorphic deposits are a definite and integral part of the hypothermal group, of which they represent a well-defined subdivision chiefly because of the special nature of the wall-rock involved. Indeed, if the contact-metamorphic ores are not the representatives of the hypothermal zone in limestones, then there would appear to be virtually no representatives of that zone in such rocks; this would lead to the quite improbable conclusion that hypothermal ores form in other kinds of rock but practically refuse to form in limestones.

Where a carbonate-rich rock is reached by a solution sufficiently vigorous chemically and thermally, the carbonate molecule, instead

of being merely dissolved and displaced bodily, as happens under less intense attack, is broken up into lime silicates and CO_2. Thus, where limestones are cut by a volatile-rich magma at high temperature, these pyrometasomatic deposits are formed right at the contact. Dependent probably on a balance between temperature and pressure, and thus somewhat dependent on depth, the deposit will be oxide-rich and sulphide poor as at Franklin Furnace, N. J.; oxide close in and sulphide farther out, as at Fierro, N. M.; or mainly sulphide-rich as at Morenci, Ariz.

But virtually identical deposits of the sulphide-rich variety may be formed in limestone distant from the contact provided the magmatic solutions reach such limestone without having lost too much of their chemical and thermal vigor en route. Retention of this necessary physico-chemical intensity, despite considerable migration, might be expected at great depth where the normal rock temperatures are high and where the intervening non-limestone rocks are relatively inert schists. Thus may be explained examples like Ducktown, Tenn., which display all the usual earmarks of contact metamorphism except the "contact." Hence Lindgren's change of name[4] from "contact-metamorphic" to "pyrometasomatic" for such deposits. At shallower horizons, where the geotherms have lower values and the non-limestone rocks are usually more reactive than are the deep-lying schists, magmatic solutions that have to travel substantial distances through such rock to reach limestone will arrive there with lessened intensity and thus will yield the more normal limestone replacements of mesothermal or even feebler character.

Vertical Range.—The vertical range of all the hydrothermal zones is probably dependent primarily upon the depth of the magma source below the then-existing surface. Where this depth is relatively small, the curvature of the depth-intensity curve will be accentuated, and each of the hydrothermal zones will be correspondingly thin, giving way with relative rapidity to the next

[4] Perhaps the significance of the change is less real than apparent; for if such ores can develop distant from the "contact" are they not equally distant from the "fire"? But if the "pyro" is justified in the sense that these are high temperature deposits, that fact would seem to be adequately covered by the term *hypothermal*.

succeeding zone. But where the magma source of the solutions lies far below the surface, depth-intensity is represented by a more slowly changing curve, each zone will be of greater vertical extent, and a much more gradual transition will be exhibited from zone to zone. Consideration of the hydrothermal deposits in general leads to the conclusion that the instances in which the solution source is deep strongly outweigh the number in which the source is shallow. It remains to define "deep" and "shallow" in other than those relative terms.

For the hypothermal zone, the maximum vertical range has never been disclosed. Probably it never will, since doubtless it greatly exceeds the depth to which man can mine. At Morro Velho, Brazil, mining has followed an absolutely continuous shoot of hypothermal ore to a depth of over 7,500 feet [5] without any indication of a systematic downward change in intensity-character. There probably is change, but the rate of change with depth must be exceedingly slow. From this slow rate, it may be inferred that, barring structural accident, the deposit must have been of substantially the same character as far above the present outcrop as mining has already reached below, and that for a further equal distance downward from the present mine bottom ore of the same general nature will continue. This would indicate a vertical range of some 20,000 ft. within which ore was deposited substantially like that now mined.

Even this great distance would not reach either to the top or to the bottom of the hypothermal zone as a whole. The Morro Velho ore is of a substantially more intense or deeper-seated type than that of Porcupine, Ontario, which is also hypothermal and already mined to 4,000 feet. Transitions at Porcupine to the Morro Velho type of ore are indicated, but there is still a considerable gap in character as yet unrepresented by known ore. On the other hand the Morro Velho ore is of less intense or shallower-seated character than that of Homestake, S. D., or of Kolar, India, in which latter district mining has already reached 7,000 feet with no systematic downward change save possibly a slight

[5] All figures of depth given in this paper refer to vertical distances. In 1933, Morro Velho had reached 8,051 feet, becoming again the world's deepest.

increase of pegmatitic streaks and clots which probably foreshadow an eventual change into an underlying pneumotectic deposit. Extensions above and below the levels mined must be entertained at Porcupine and at Kolar without substantially changing the character of the ore of either of those localities.

If it be imagined, then, that the Morro Velho deposit be set on top of the Kolar deposit and the Porcupine veins set on top of both, with intervening gaps to represent transitional characters not represented in any of the three districts, we would have indicated an aggregate vertical range of perhaps 50,000 ft. for the hypothermal zone. Even this might not be a maximum. On the other hand, no such great range may actually have existed at any one place. The accidents of structure and rock character are rather against it. But I see no valid objection against the *possibility* of so great a range; and in single occurrences a vertical span of half that distance, or say five miles, may be common enough if we could but know all the facts. If magmas can exist and can undergo crystallization to igneous rocks at depths of ten or twenty miles in the crust, then I see no reason why hypothermal deposits may not extend down to depths as great.

The specific examples of great vertical persistence that have just been mentioned fall in the structural category of veins or lodes and are of relatively restricted horizontal cross section. As contrasted with such steep lodes, extensive replacements of greater horizontal dimensions would be expected to have a smaller maximum vertical range within the hypothermal zone,[6] because of greater dissipation of the solutions and thus more rapid reduction of their physico-chemical intensity on their upward journey.

So much for the maximum range. The minimum vertical range of the hypothermal zone is likewise probably unknown, for there appears to be no well-authenticated case in which mining has passed downward from the bottom of the mesothermal zone to and beyond the bottom of the hypothermal zone. For the hypothermal zone as a whole, the rate of change in mineral and textural character downward is almost undiscoverably slow.

[6] The same contrast would of course hold true in any of the zones.

The Mesothermal Zone.

General Characteristics.—The mesothermal zone begins at such elevation or such distance from the parent source that the physico-chemical conditions cause the deposited material to show departures from those characteristics which we call hypothermal and acquisition of new characteristics to be classed as mesothermal. The boundary line between the two zones, as in most natural series, has to be placed arbitrarily. No reason appears for changing Lindgren's placing of it.

Deposits of the mesothermal zone are highly varied in detail, but they all have the earmarks of deposition under those intermediate conditions of intensity of which the prefix "meso" is expressive. As contrasted with the hypothermal, the mesothermal zone shows, besides a well-recognized difference in mineralogy (the quartz is milky, never approaching clear and glassy as in some of the deepest hypothermal ores), a tendency toward decrease in proportion of veins to extensive replacements, an average decrease in grain size, somewhat more of vugginess, occasional crude and coarse banding in the veins, and marginal rock alteration that is more readily identifiable as such.

Vertical Range.—Lindgren says: "A great vertical range of up to 5,000 feet or even more is characteristic of many types described under this (mesothermal) heading. . . . Many of them continue to the greatest depths reached in mining." The maximum range for the zone as a whole must plainly be greatly increased. On the Mother Lode, Calif., mine levels more than 5,000 ft. deep are encountering almost identically the same kind of ore that occurs just below oxidation. All this ore obviously belongs toward the deeper end of the mesothermal range. But here again the extremely slow rate of change through this explored span obviously requires that relatively great overlying and downward extensions of essentially similar ore must be granted.

The great conglomerate lodes of the Witwatersrand, Transvaal, confirm the testimony of the Mother Lode through an even greater depth range, provided the abundant evidences of hydrothermal origin at the Rand be accepted as conclusive. In that

district mining has now gone to a vertical depth of 7,800 feet [7] without disclosing any systematic change in character or quantity of deposited minerals save probably a slight falling-off in the most minute component, gold—a falling-off difficult to establish with certainty because of the obscuring influence of non-geological factors on the production records through the years. This known Rand ore with its indefinite upward and downward extensions of similar character should probably be placed toward the lower boundary of the mesothermal range. It shows but faintly and only sporadically those features which would indicate transition toward the hypothermal zone and nothing whatever of the characteristics that would suggest proximity to the upper boundary of the mesothermal range. An original vertical span of 20,000 feet for ore of the kind now known on the Rand seems not at all unreasonable.

The Morning Lode in the Coeur d' Alene District, Idaho, has been opened continuously to just short of a mile below the outcrop. It is a lead-zinc-siderite ore, with scanty barite, and belongs not deeper than the upper half of the mesothermal group. The ore is substantially constant in character from top to bottom of the mine. At the Bunker Hill and Sullivan Mine a few miles distant, a vertical span only slightly smaller is opened on ore of shallower-seated characteristics than that of the Morning Mine.

From such examples as these, it seems necessary to conclude that the maximum range of the mesothermal zone surely exceeds 10,000 ft. and in individual occurrences it may have possessed a 20,000 ft. range or even more. The minimum range is less readily to be stated, but rare indeed is the case in which a given mine has spanned the entire vertical mesothermal range by passing downward from material belonging above the upper limit to material belonging below the lower limit of the zone.

The Leptothermal Zone.

Definition and Characteristics.—While realizing the dangers of coining new terms, of redefining old ones and of taking liberties

[7] Early in 1933, the Turf or old Village Deep section of the Robinson Deep property had reached a vertical depth of 8,006 feet, but is now surpassed by Morro Velho, Brazil.

with classifications already familiar, nevertheless I venture to propose for consideration the establishment of a new zone, for which is proposed the name *leptothermal* from the Greek *leptos* implying moderate or subdued. The leptothermal zone comprises a part taken off the top of Lindgren's mesothermal and a part off the bottom of Lindgren's epithermal, and thus stands between those two as necessarily redefined.

The characteristics of this proposed zone are revealed in well-known vein occurrences such as certain of those in the San Juan Region, Colo., Sales's outermost zone at Butte, Mont., Casapalca, Peru, and as somewhat variant types, the Michigan copper lodes and the veins of Cobalt, Ont. But the essential genetic features of the zone appear also in replacement bodies in limestone or in other rocks susceptible of rather easy attack.

Metalliferous minerals include both the simple sulphides so abundant in the mesothermal zone and more complex sulphide molecules and sulphosalts of the base metals and of silver. But the silver-bearing minerals generally either are not of the richer varieties or are present rather scantily, and the silver is commonly a by-product of base-metal production rather than dominant on its own account. Gold in the metallic form or as telluride is ordinarily subordinate. Of the metallic minerals diagnostic of the deeper zones, only specularite occurs and infrequently. Milky quartz generally dominates as gangue, but is commonly associated with more or less carbonate or barite; less commonly with fluorite or with adularia as indicative of transition toward epithermal. The carbonate mineral is prone to be manganiferous and is often rhodochrosite, not uncommonly accompanied by some rhodonite. Where gabbroid magma is the source, quartz is less in evidence than carbonate, and silicates derived from the immediate walls may appear.

Grain size, while rarely fine, averages smaller but more variable than in mesothermal ores. In the veins, coarse banding or crustification is likely to be strikingly developed, but may become interrupted and irregular or entirely disappear. Vugs and druses are common. Angular fragments of wall rock become increasingly noteworthy in the veins toward the shallower limit of the

zone and, by complicating the vein channelway, favor incomplete filling and thus increased development of vugs. Rock alteration, generally not very pervasive, varies in the average wall rock from sericitic, like that so characteristic of the mesothermal zone, to the propylitic phases common in the epithermal.

Vertical Range.—The vertical range of the leptothermal zone is probably less than that ascribable to either mesothermal or hypothermal. The supposition that the long-sought transition from one zone to another might be revealed by the great topographic relief of the San Juan country has recently been embarrassed by Burbank's convincing proof at Ouray that the lower deposits antedate and are genetically independent of those present in the higher mountains. Correlation from top to bottom of all the Ouray deposits as if varying parts of a genetic unit is thus fallacious. Nevertheless, where mining has been carried deep enough in the younger deposits, a marked change in character is discernible in the selfsame veins, as strikingly shown, for example, in the Camp Bird Mine. The lower part of such veins shows definitely leptothermal characteristics; the upper part is typically epithermal in the narrow sense used here. Although this appears to afford an undoubted transition from one zone to another, the full vertical range of neither zone is revealed.

A better indication of the range of the leptothermal zone is afforded at Casapalca, where vertical development of the same vein system now reaches nearly 4,000 feet. In the uppermost few hundred feet, transitions toward epithermal character have just escaped erosional destruction. Thence downward, as McKinstry and Noble have shown, one sees the characteristic mineralogy of the leptothermal zone, which is still continuing strong in the mine bottoms. However, a slow but undoubted change in mineralogical character and metal content from outcrop to lowest level forewarns that at some still greater depth the deposits will begin to resemble the upper mesothermal veins and replacement deposits present in the central part of the near-by district of Morococha; in these latter, enargite is a distinctive mineral, but some marginal occurrences with tetrahedrite and rhodochrosite are suggestive of leptothermal. At Casapalca, then, one may

estimate that the exposed vertical span of over 3,000 feet in the leptothermal zone represents something like half of its total range in that district.

Deposits of the general character of those at Cobalt are at present less certainly to be included in the leptothermal group. But as I appraise their physico-chemical and genetic significance, they seem to belong at this place in the hydrothermal range rather than at any other. The probability that such deposits come from a magma source of more basic composition than those which furnish most of our hydrothermal illustrations may account for the abundance of cobalt, nickel, arsenic and native silver. Silver-rich sulphides and sulphosalts at certain outlying points of the district suggest an unimportant peripheral zone of epithermal character.

The native copper deposits of Michigan, unquestionably hypogene and hydrothermal, may belong here. They have almost nothing in common with hypothermal or mesothermal ores and relatively little in common with the strictly epithermal deposits save a dominant marginal alteration leaning strongly toward propylitic. The presence of arsenides and of native silver hints at analogy with deposits of the Cobalt type. The fact that copper occurs almost wholly as native metal plainly results from oxidizing effects of the hematite-bearing wall rocks and therefore is not to be taken as an independent characteristic of the zone to which these deposits belong. The virtually constant character through 6,000 feet of vertical development on single lodes in the Quincy and the Calumet and Hecla mines confirms the very substantial thickness of this leptothermal zone, for these lodes have undoubtedly suffered great erosion and their extensions below the present mine bottoms reach to depths beyond forecast. Broderick's interesting disclosure of certain restrained indications of downward change for the district as a whole serves also to emphasize the great vertical persistence of these Michigan deposits. At Corocoro, Bolivia, the notably similar deposits may be of somewhat shallower formation than the portion of the Michigan lodes now known, *i.e.*, they may be the depth equivalent of portions of the Michigan deposits now eroded away; but it

seems clear that the solutions at Corocoro had travelled less far in the red, oxidizing rocks and therefore the proportion of native copper to copper sulphide is lower in Bolivia than in Michigan.

The maximum vertical range for the leptothermal zone may be estimated as of the order of 10,000 to 15,000 feet at least. The minimum thickness may be much less; but again no clear-cut examples come to mind in which vertical development has passed through the entire leptothermal range.

The Epithermal Zone.

General Characteristics.—As it remains after its former lowermost portion has been contributed to leptothermal, the epithermal zone shows vein structures likely to be strong and well-defined at first but prone to branch and complicate upward, as at Comstock Lode, Nev. Still shallower, such structural complexity may increase. This is shown strikingly at Goldfield, Nev., where the ascending solutions, when reaching within a relatively short distance from the then-existing surface, abruptly spread out from their former more restricted channelways into nearly every available fracture in the highly shattered effusive rock.

Vugs range from scanty to very abundant, depending chiefly upon the degree of irregularity of the available openings, which in turn depends largely on whether or not the fractures contained jumbled fragments and slabs fallen or exploded from the walls or even flushed up from below by the velocity of the solutions. The common banding due to successive depositions is on a finer scale than in the leptothermal zone, and frequently is curved and scalloped rather than straight. The fashion just now prevailing names this sort of banding "colloform" and invokes colloidal deposition as its cause. The microscope, however, seems to show little to support and strong evidence against colloidal phenomena in most of these fine-grained deposits. The common fineness of grain of both gangue and sulphide minerals is doubtless a direct expression of the rapidity with which saturation was attained and crystallization induced by the ultra-rapid loss of heat and pressure experienced close to the surface. But just as in the leptothermal ores, grain size varies abruptly.

The well-known mineralogy of the typically epithermal ores is a natural progression from that of the leptothermal. The silica ranges from milky quartz through porcellanic, flinty and dull cherty, to opaline varieties. One of the most noteworthy mineralogical characteristics of this zone is the generally low ratio of metalliferous minerals to gangue.

The greater number of representatives of the epithermal zone indicate by their mineralogy and attendant rock alteration, just as in the lower zones, that they were formed by alkaline solutions. But in some the ascending solutions eventually become acid. To accomplish this, a means probably more competent and more restricted to this definitely shallow region would be required than the interesting proposal by B. S. Butler for sulphate formation by abstraction of oxygen from ferric compounds. This means would seem to be afforded in the reaction established by E. T. Allen whereby in a closed tube at 200° C. liquid water and sulphur yield sulphuric acid:

$$4H_2O + 4S = 3H_2S + H_2SO_4.$$

The conditions of this reaction appear to accord well with the conditions of temperature, pressure and composition likely to prevail in the very upper part of the hydrothermal range. The consequences would be postulated as follows: If and wherever the proportion of acid so produced in the solutions exceeds their natural inherent alkalinity, they will thenceforth fail to deposit carbonates and will attack any carbonate that may previously have been precipitated at or above the level where the change to acidity takes place. Thus may be explained the hackly or lamellar quartz so common in epithermal ores. They will also fail to deposit adularia, a mineral common in epithermal ores of alkaline environment. Where the acid concentration becomes still stronger, definite attack will be made upon the alkaline silicates of the wall rock; in this way the kaolin mineral, dickite, and, with still higher acid concentration, the sulphate-rich alunite, may result. And it may be that the relative instability of many of the silver-bearing sulphides in H_2SO_4 has to do with the dominance of gold over silver in those very shallow epithermal

deposits where hypogene acid attack seems to have been strongest. For such very shallow-seated examples as Goldfield, Nev., Red Mountain and Cripple Creek in Colorado, as well as the Lassen * and the Yellowstone hot springs, one must agree with Larsen that the responsible acid is to be regarded as wholly of hypogene origin. That it resulted from atmospheric oxidation, as some have proposed, seems quite incompatible with the attendant geological facts. This extreme of acid development in the hydrothermal waters probably takes place only under rather uncommon circumstances. It is also probably attained only fairly close to the surface. There is even the possibility that it may be coincident with that occasional change of the solution from a dominantly liquid to a more or less gaseous state through rapid loss of pressure close to surface.

Vertical Range.—The epithermal zone as here defined probably has a smaller vertical range than any of the three already discussed. Perhaps the most conspicuous evidence of this is the fact that many profitable mines on these epithermal ores become unprofitable within a depth of one to three thousand feet from the present surface, although in many instances the veins on the bottom levels may continue as wide and even as long as above and may contain 95 to 99 per cent. of the same minerals as in the profitable levels, the small percentage of change having unfortunately affected chiefly the precious metal content. Obviously, economic death is not necessarily coincident with termination of the genetic type. Therefore, this oft-observed decline in commercial tenor is not so convincing an indication of the relative thinness of the epithermal zone as is the common downward change in mineralogical and textural character that is to be seen in most mines a thousand or more feet deep on these epithermal ores, even though commercial values may still persist.

The Comstock deposits, opened vertically for more than 3,000 ft., are still above the leptothermal zone, even though the lower levels were unprofitable. At their present outcrops, however, the Comstock ores are clearly deeper-seated representatives of the

* Not seen by the writer.

epithermal zone than are, for example, the ores of Tonopah, and still deeper than those of Mogollon, N. M., Republic, Wash., Cripple Creek, and particularly Goldfield. It would, therefore, appear justifiable to assume that the Comstock veins initially extended two or three, or even more thousands of feet above their present outcrops. Such an indicated total of, say, 6,000 ft. at Comstock is possibly greater than the general average for this zone; but there is no good reason for thinking that this particular district embraced the maximum possible range for the zone.

The so-called barren zone into which the profitable epithermal ores so often pass when developed downward involves no real mystery. These richer ores generally have abundant gangue and subordinate quantities of sulphides and other metalliferous minerals. Because of the extremely high ratio of value to weight possessed by silver and gold, these metals when occurring as a wholly insignificant percentage of the total mineral mass suffice nevertheless to give a rich ore. The normal genetic expectation is that these precious-metal epithermal ores will gradually pass downward into coarser-grained sulphide-richer ores in which the common base metals predominate, such as found in the leptothermal zone. But the base metals have so low a ratio of value to weight that a relative abundance of base metal sulphides is required for an economic ore. Therefore, as the ore changes in character downward, the base metals would have to increase scores to thousands of times as fast as the precious metals fall off if the same money value of the ore is to be maintained throughout.

No such abrupt change in proportions of mineral deposition is to be expected as the usual thing. Instead, it is likely to happen that in the gradual change from dominantly precious metal ores above to dominantly base metal ores below, there will be a stretch where neither the precious nor the base metals, nor indeed the combined value of both, meets the economic requirement. Therefore, mining ceases before the complete transition has been disclosed. But in a few favorable regions this unhappy economic limitation upon geological observation does not apply. For example, in the veins at Casapalca, the gradation from epithermal

silver ores as the uppermost portion left by erosion to lepto-thermal base metal ores with silver as a by-product fortunately holds steadily above the economic requirement and, therefore, the transition from zone to zone finds opportunity and incentive to be revealed by mining operations.

Telescoping, Pre-Heating and Stretching.—The notably rapid change in characteristics of ore with depth in many of these deposits of shallow-seated deposition is given by Spurr the expressive term " telescoping " and by Niggli referred to as " crowding." Spurr ascribed this to a peculiar breakdown of the " ore magma " close to the surface; and by thus magically disposing of the ore magma, he managed to escape the otherwise damaging absence of " ore lavas," and " ore tuffs," that is, surface effusions of ore magma corresponding to surface outpourings of rock magma. Telescoping probably represents merely hurried and promiscuous precipitation caused by rapid loss of heat and pressure as the ascending solutions are dissipated into the highly fractured and colder rocks near the surface. That the temperature and pressure gradients are excessively steep close to the surface in volcanic regions is indicated by the " steam wells " and analogous occurrences in various parts of the world and by the results of recent drilling by the Geophysical Laboratory party in Yellowstone Park.

If it should prove true that somewhere within a few hundred to one or two thousand feet of the surface the hydrothermal solutions in certain districts experience such faster loss of pressure than of heat that there is substantial conversion from their previously liquid state into the gaseous, the decreased solvent power of water as steam and the cooling due to the latent-heat effect might cause an abrupt dumping of solutes where such change of state takes place and thus produce a highly exaggerated manifestation of telescoping.

It seems probable that telescoping is especially likely to occur where the geothermal gradient is abnormally steep because of the near-surface cooling of hot effusive rocks that had but shortly preceded the introduction of the ores. In such instances the solutions would have moved upward for indefinite distances along

"pre-heated" channelways, losing heat less rapidly than they would if passing through rocks where the usual thermal gradient prevails. In so far, therefore, as rate of heat-loss affects mineral precipitation, solutions under these circumstances would cause deposits characteristic of the deeper zones to be extended, or "stretched" as one might say, to abnormally shallow levels. But in close proximity to the surface, where the preceding effusives have become cold, the rate of heat-loss by the solutions will be so unusually rapid as to produce impetuous deposition which telescopes or crowds together kinds of minerals that should under more normal circumstances have been deposited successively at different places along the ascending pathway. Naturally, in some districts telescoping evident below the present erosion surface will be unimportant; in others it may be highly exaggerated. Indeed, where the pre-heating has been accomplished or augmented by an intrusive body reaching close to the surface, telescoping may be so extreme as to bring minerals characteristic of great depth up to those shallow levels where normal epithermal ores would naturally be expected. For example, F. S. Turneaure, holder of the Emmons Memorial Fellowship for 1931–32, finds that at Llallagua, Bolivia, cassiterite, wolframite, tourmaline, pyrrhotite, and arsenopyrite were thus deposited in and about a porphyry stock at surprisingly shallow depths; and in the same district Lindgren has described a present-day hot spring that carries tungsten in what would otherwise be regarded as anomalous association with barium and manganese.

The growing number of occurrences in which complexity of sequence and mineralogy is ascribed, both here and in Europe, to depositions of different ages and characters at the same locus plainly should not be called examples of telescoping, unless that term is to suffer confusing distortion from its original meaning; superimposition or "rejuvenation" (Berg) would seem better to imply what is intended. Moreover, it appears probable that many of the instances to which is now assigned such a "heterogenetic" (Niggli) history will be proved by further consideration and study not to be haphazard consequences of chance positional coincidences of unrelated depositions; but instead will be

found to be entirely understandable manifestations of mechanical and physico-chemical readjustments that inevitably result from changing conditions during a single but extended and complex mineralizing process attending a given period of igneous activity.

Source.—The common occurrence of these epithermal deposits in regions of Tertiary effusive rock has led some to believe that they have a shallower-seated source than do the ores of the deeper zones. Conformable with the long-standing distinctions of the German petrological school between "old" and "young" igneous rocks, Niggli, Schneiderhöhn, and Berg severally undertake, indeed, to distinguish and separate plutonic or intrusive from volcanic or effusive types [8] of ores, and in the latter category they place the epithermal deposits. But as both Lindgren and Kato have emphasized in reply, as a result of their long and intensive first-hand studies of this type, derivation of the epithermal ores directly from the masses of the effusive rock is extremely unlikely. That the Tertiary volcanic rocks and the epithermal deposits which cut them have a related parentage may be granted. But this is far different from assuming that metals and volatiles, brought up to shallow levels as undifferentiated components of molten material shortly to be ejected as flows and tuffs, will be liberated with that restricted localization required to produce economic ores. Instead, hopeless dissipation as sublimates, fumarolic incrustations and insignificant "exudation veinlets" would be vastly more probable than effective concentration. In a region like Casapalca, where strong productive veins pass uninterruptedly from underlying sediments up into effusive rocks and eventually change from leptothermal to epithermal character, a deeper-lying source of the solutions is surely indicated than the surface volcanics themselves. In still other districts, some of which will be mentioned hereafter, ores of close affiliations to epithermal, if not actually belonging in that subdivision, occur in sediments of regions where apparently there have never been surface effusions

[8] Since this manuscript was written, Schneiderhöhn has expressed views (Zeit. prakt. Geol., 40, Heft 11, p. 2, 1932) that may indicate some misgiving on his part as to the distinction between intrusive and extrusive affiliations for the hydrothermal ores.

of corresponding age. On the other hand, I see no reason for assuming, as Lindgren appears to do, that the epithermal ores came from even deeper magma sources than those which yielded the leptothermal and deeper zones.

Although it is probably to be recognized that some epithermal deposits represent a somewhat abnormal bulge in the otherwise generally smooth line of progression from zone to zone throughout the hydrothermal range, or may in some instances perhaps even be regarded as a separate split off the main line of throughgoing relationships, these aberrations must be attributed, not to differences in source, but to differences in the local environment at and near the place of deposition, resultant probably in greatest part from the highly permeable condition of the effusive rocks and from the unusually steep thermal gradient close to the then-existing surface. There seems every reason to suppose that the leptothermal, mesothermal and hypothermal zones underlie the epithermal just as these zones successively underlie one another.

The Telethermal Zone.

Definition and Character.—There is now wide-spread belief that the hot springs and geysers of many regions represent the surface discharge of solutions which, below their outlets, are performing mineralization of the epithermal kind. Such escaping solutions still have mechanical, thermal, and chemical energy which they dissipate and waste on pouring out at the surface. In other words, it would seem that the epithermal deposits do not necessarily mark the complete upward exhaustion of the capacity of the solutions to accomplish mineral deposition; they do not represent the logical termination of the hydrothermal family.

The question therefore arises: what kind of deposits, if any, stands at the very terminus of the hydrothermal lineage? That is to say, what will happen in a region where a great body of hydrothermal solution ascends through rocks not abnormally "pre-heated" by just-preceding vulcanism, but where instead the normal thermal gradient prevails? In due course upward the solution in such a region would deposit the successive min-

eral zones up to and including the epithermal, or at least some non-telescoped intensity-equivalent of the epithermal. But after it had finished the deposition of such products, it would still retain thermal, piestic and chemical power, though of reduced intensity. It might still be some distance below the surface and be destined to continue on upward to a place of easy outlet.

It seems reasonable to assume that such enfeebled hydrothermal solution passing through relatively inert rocks of aluminous and siliceous composition is likely to experience little stimulation of its flagging powers, and thus leave behind little in the way of depositional evidence of its passage through such rocks or of its existence at all. But if it should pass into rocks more highly reactive, particularly into limestones, these might be able to exact from the tired solution all that it has left to give. (This is, of course, no novel principle invented to support the particular proposal just made; from the pyrometasomatic deposits on upward into the great mesothermal and higher replacement bodies, aggressive attack is made selectively on limestones while adjacent more resistant rocks are relatively ignored.) At favorable places, the quantity of solution available and of solute capable of deposition by reaction with the susceptible wall rock may suffice to produce deposits that are large, but they are bound to be of the lowest order of intensity in the physico-chemical sense.

Deposits possessing the position and the characteristics that the foregoing considerations of genesis would imply are, of course, well known. It is proposed that they be called *telethermal*[9] to indicate their direct affiliation with the hydrothermal family. Long ago the French geologists referred to certain of the components in deposits of this kind as the "far-travelers." The "apomagmatic" group of present-day European geologists would include these telethermal deposits, but, as a mere contrast to "perimagmatic," the name seems too indefinite to specify this particular zone. Some of the same deposits Niggli calls "telemagmatic"; his term has priority over "telethermal," but seems less expressive of the *serial* relationship of these deposits to those of the other hydrothermal zones and is, moreover, definitely re-

[9] Name suggested to the writer by a former graduate student, C. G. Doll.

garded by him as implying a basic magma source—an idea which, however attractive, is by no means yet proved.

The outstanding examples of the telethermal zone are the lead-zinc deposits of the Mississippi Valley and similar occurrences in many parts of the world. As a long-time believer in the hydrothermal origin of the Mississippi Valley ores, I listened with deepest satisfaction to a recent Presidential Address before this Society by Professor W. H. Emmons, in which he supported the magmatic derivation theory chiefly through the evidence he adduced of zoning in that extensive province. It must be confessed that, when actually on the ground, the zoning part of this conception seems in certain directions rather less convincing and secure than when one reads it in print; it may prove that certain occurrences which Emmons has cited as fitting into and strengthening the zonal pattern are in reality independent in age and genesis of the major lead and zinc deposits. But some of his evidences of zoning are indeed difficult of escape.

Moreover, as both Pirsson and Spurr had noted, the general aspects of the deposits both in southeastern Missouri and in the Tri-State region seem wholly familiar to one accustomed to hydrothermal sulphide deposits. No single item of composition, mineralogy, sequence, texture or structure of those deposits fails in my opinion to find approximate counterpart in many examples of undoubtedly hydrothermal origin. Were the Mississippi Valley ores to be just now discovered, it seems probable that their classification as a subdivision of the hydrothermal family would be made unhesitatingly by all, since interpretation would thus entirely escape the influence of that long inheritance of local tradition favoring meteoric origin, which started before there existed the present adequate and consistent philosophy of magmatic derivation of sulphide ores, and which in large measure built itself up to fit only these particular deposits among all the sulphide ores of the world. One may look forward with confidence to the time when American opinion with respect to these mid-continental deposits will be as unanimous as European opinion has become regarding analogous occurrences elsewhere.

Into this telethermal class may be put the so-called "red bed" copper deposits, such as those of the southwestern United States,* where calcite cement of the sediments seems to be the chief victim of replacement by the copper sulphides. Here, also, may be placed provisionally the Broken Hill lead-zinc deposit of Northern Rhodesia, whose important vanadium content suggests that other puzzling vanadium and uranium ores may belong likewise in this or a nearby category.

Perhaps just at the lowest limit of this zone belong the rich copper replacements in limestone of Kennecott, Alaska, before they were affected by supergene processes, and those of Katanga, in the Belgian Congo, before they were so profoundly modified by the peculiarly intense tropical oxidation. Deposits closely related to the latter, and lying just to the south in Northern Rhodesia, but occurring for the most part rather in shaly than in limy rocks, possibly belong a little deeper in the hydrothermal range.

The mercury ores, with which I have almost no personal familiarity, may perhaps belong somewhere near the border line between the epithermal and the telethermal zones in those regions where there was some manifestation of intrusive or extrusive pre-heating of the channelways and where the solutions retained enough vigor to attack non-limestone rocks.

On the whole, the base metal and metalloid sulphides of this zone are strikingly deficient in precious metals, though occasional exceptions appear. Nickel and cobalt may be sparingly present, suggestive of affiliations with leptothermal ores. Cadmium often accompanies the zinc, as it is now being found to do in certain mesothermal and hypothermal deposits. Fluorite and barite are present here and there, indicative of epithermal relationships. In the typical telethermal deposits there was leisurely deposition rather than that impetuous dumping so characteristic of the epithermal ores. Therefore, the grain size of the sulphides usually ranges from medium to coarse, especially where the replaced rock has the low resistance of calcite and dolomite; but concentric

* The writer has examined some of these deposits in New Mexico and Arizona, but not elsewhere.

banding (Schalenstruktur) due to successive deposition of differing thin layers is noteworthy in some occurrences; moreover, most of the silica occurs with characteristic fine grain, often cryptocrystalline and cherty like that in the shallowest epithermal ores. Marginal alteration is as a rule insignificant or wanting because nothing can be much feebler than these deposits themselves.

Vertical Range.—The indicated low physico-chemical intensity of these telethermal deposits is compatible only with the view that they were formed at no great depth below the surface. On the whole, indications from the local erosional history appear to confirm this conclusion. Perhaps 3,000–4,000 feet might be assumed as the maximum vertical range of the zone. Inasmuch as any deposition of importance is generally dependent on encounter by the solutions of favorably reactive rock, the vertical dimensions of individual telethermal deposits are likely to be much less expressive of the vertical range of the zone than they are of the chance local thickness of the favorable rock formation. For the same reason, these ores may appear to terminate abruptly and permanently downward at the place where the favorable formation gives way to an underlying formation of unreceptive character, since the local vents or channelways of ingress from which the solutions spread out into the favorable formation may be relatively few in number and of restricted cross section, and they may even be, when at last brought to view by mining, so faintly marked by deposited mineral material as to escape recognition for what they actually are. This same paucity and insignificance of feeding channels from below is, of course, common in limestone replacements of all the zones, although exceptions occur.

CONCLUSIONS.

The foregoing consideration of the hydrothermal deposits presumes to link on where the pneumotectic operations cease, and to carry through thence to the place of ultimate discharge, at or near the surface, a reasonably consistent but changing sequence of events. It proposes to add to the hydrothermal family a number of types previously treated as somewhat special and disconnected cases, but which seem actually to fit consistently into a

unified series. Thus the contact-metamorphic or pyrometasomatic deposits, the fahlbands and related pyritic masses hitherto commonly linked with regional metamorphism, the deposits of native copper (and associated sulphides), the lead-zinc deposits of the Mississippi Valley type, the copper deposits of the "red bed" and Katanga types and similar occurrences often entertained as syngenetic, as well as many miscellaneous metalliferous deposits ascribed by Lindgren to "circulating waters" find by this view logical ascription to direct magmatic ancestry. Together with the orthotectic and the pneumotectic concentrations, the hydrothermal family thus embraces all known types of sulphide ores save only the supergene rearrangements.

The possibility that with further study we shall be able to recognize more or less parallel lines of descendants, depending upon whether the immediate magmatic parent was dominantly basic, intermediate or salic, must be left alluringly open, though with the probability that, for the hydrothermal ores, a magma which yields igneous rocks rather on the salic side of intermediate is likely to be most prolific.

Form of deposit enters into such a genetic classification only as an accident of the environment or in consequence of depth conditions with which, through temperature and pressure, chemical equilibrium must deal.

No provision seems necessary for any genetic differentiation on the basis of age, which has so long been emphasized by the German school, or on the basis of whether the related rock did or did not break through to the surface. Possibly the deep-lying sources are with the passage of time being gradually exhausted of their volatiles and their metals, and thus there may exist a progressive change in quantity and character of ores from early to late geological time. But we are as yet unprepared with specific data whereby to check this idea.

The basis for subdivision of the entire hydrothermal lineage into a number of zones is intended to be primarily physicochemical; these zones are in reality *intensity-zones*. But since we have as yet no direct way of measuring absolutely the physicochemical conditions that prevailed nor the changes they experi-

enced from place to place, we must reach inferences regarding them from what resulted in the way of mineral deposition and rock alteration at these various places. For so doing, I follow Lindgren in the view implied by his first naming of the hydrothermal subdivisions as deep, intermediate and shallow; namely, that the simplest and probably the best integration of all the variables is by means of the yardstick of depth. Depth pretty directly affects pressure on the solutions; depth, in the sense of distance of flow through rocks cooler than the solutions, affects their temperature; and in the sense of distance of flow through reacting wall rocks, depth affects composition of the solutions. But it is, of course, to be clearly understood that depth as so used is relative, not absolute. Thus, in any given occurrence, increasing depth almost invariably means increasing intensity; but a given nature of ore, representing a certain intensity factor, may have been formed at somewhat different depths in different occurrences. Moreover, one of the vital factors affecting deposition, namely, rock character, may be highly independent of depth, and especially where limestones are involved there may be striking accelerations of the otherwise normal tendencies.

The figures hitherto assigned for the maximum vertical ranges of the several hydrothermal zones must evidently be greatly increased, so that if the probable maximum for each of the five subdivisions here contemplated be added, one on top of another, with appropriate allowance for overlap, the aggregate might conceivably be of the order of one hundred thousand feet, or say twenty miles. No reason is apparent, whether in erosional history or magmatic process, for recoiling from so great a figure, though on the other hand it seems probable that in the average individual case the total hydrothermal depth range was much less, because of shallower location of the magma source. In a broad way, each higher zone tends to be thinner than the one next below; but the local environment may in some places upset this general tendency.

No reason is evident for excluding the possibility that substantial deposition may take place along a continuous channelway system from the lowermost end of the hypothermal to the

uppermost limit of the telethermal zone. On the contrary, there is no requirement that deposition must persist uninterruptedly throughout such a channelway system. Indeed, experience shows that certain oreshoots of the kind called by Irving "shoots of occurrence" terminate completely, and then at some greater depth other such shoots may recur. How great the longest of these intervening gaps may be, we do not know. Some of the zones, at a given occurrence, therefore, may be entirely unrepresented by deposited mineral.

Just as Lindgren's range of depths must probably be increased, so must the temperatures he has assigned for the various zones probably be in general marked up to somewhat higher values. The relatively few points already established on the so-called geological thermometer have, for the most part, been ascertained under highly simplified laboratory conditions. It is gradually being demonstrated, as some had already surmised, that when the conditions are actually as complex as those which prevail in nature, the tendencies in many cases are to raise the temperatures over those which obtain under simple conditions. For example, the critical temperature of water at 374° C. and the beta-alpha inversion point for quartz at 575° C. are repeatedly used in geological discussions as if absolute and unchanging, like two plus two. But we have learned that the critical temperature may be greatly elevated by dissolved solutes; and that the quartz inversion point may probably be raised 100° or more by the pressure in the deep zones. With the temperatures of possibly superheated magma at one extreme and the high present-day temperatures running into hundreds of degrees found at or close to the surface in the Yellowstone, the Katmai * and similar hot-spring and fumarole regions, where underlying batholiths are undoubtedly now crystallizing, it seems probable that the vast majority of hydrothermal deposits have been formed far above the temperature of boiling water at the surface. For the telethermal deposits alone can really moderate temperatures be assumed.

Let it not be overlooked that the purpose of classification is not to set forth final and indisputable truths but rather to afford the aiming-sights for prediction and the stepping-stones toward bet-

ter understanding. Nor should it be forgotten that the difficulties and dangers which inevitably attend every effort at classification of such varied and complex phenomena as mineral deposits must apply to the groupings and the highly abridged generalizations presented in this paper. The extension and increasing precision of field observation, the improvements in microscopical and other instrumental technique, and the further invaluable advance in physico-chemical experimentation will gradually, here as in other problems, separate the evanescent from that which merits survival.

My obligation is great to many fellow geologists whose spoken or written ideas have contributed to the viewpoints expressed herein, both in ways that are definitely remembered and can be acknowledged and in those more subtle ways that do not always come specifically to mind yet have none the less become a part of my understanding and beliefs.

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RÔLE OF WATER CONDITIONS IN THE FORMATION AND DIFFERENTIATION OF COMMON (BANDED) COALS.[1]

DAVID WHITE.

INTRODUCTION.

THAT coals of the common kinds, regardless of their rank, are evolved from peats is a fact now well established and generally accepted. Also, the facts that common banded coals were laid down as peats, mainly of the lowland swamp type, and that they are for the most part derived from vascular (fibrous or woody) subaerial plant growth, as shown both by the geological environment and the megascopic characters of the deposit, are now definitely confirmed by the microscopical study of the coals themselves.

The purpose of this paper is to show that in the normal banded coal bed, the laminæ, the proportions of the organic components as they change from layer to layer, and, to a great extent, even the type of coal, depend upon the water of the peat-forming area, and its changes.

In this discussion only the formation of peat, and the biochemical decomposition products of the microbian activities which convert plant substances into peat, are concerned.[2] The transformation—actually the metamorphic evolution—of peat into coals of successively higher ranks through geochemical changes, geodynamically influenced, by which the progressive carbonization of the organic matter is accomplished, will not here be considered, since it does not affect the type of the coal nor the quantitative relations of the so-called components.

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] For a more complete discussion see White, David, in Treatise on Sedimentation, by W. H. Twenhofel and collaborators (The Williams & Wilkins Co., Baltimore, Md.), 2d ed., p. 353, 1932.

RELATION OF THE WATER TO OTHER FACTORS.

In the formation of peat the initial rôle of the water is to envelop or cover the falling vegetable debris and exclude atmospheric oxygen, thus impeding or even arresting the process of decomposition, according to the conditions obtaining, as will presently be discussed. Also, the water tends to stabilize the temperature at the surface of peat formation, acts as solvent, furnishes a medium for microbian and other plant growth, suspends, confines, and even concentrates or may dissipate the liquid biochemical decomposition products, besides serving as a carrier of debris, microbes, and chemical matters.

Other collateral factors affecting more or less directly the formation of coal deserve orientation in this connection, though they are generally more or less well known: (*a*) the topography, which must not slope so steeply as to permit the vegetation-impeded water to run off, while the substratum must be sufficiently impervious to prevent downward escape of the water; (*b*) the air temperature, which hastens the rate both of plant growth and of plant decay when warm, and retards both when cold,[3] but is most favorable when equably warm and uniform; (*c*) the rainfall, which is best when well distributed through the year and sufficient to maintain the optimum water level in the area of peat formation,[4] since dry seasons or periods of drought, though favoring concentration of toxic biochemical products, and so the conservation of a larger proportion of the ingredient debris if they are not too dry, may permit evaporation of the water to too low a level, with consequent exposure and oxidation of the peat surface,[5] and even a net loss of peat if they are too prolonged, while, on the other hand, the precipitation must not be so heavy as to flush

[3] Cold sufficient to arrest all microbian action also arrests effective plant growth.

[4] Peat would now be forming in many areas or environments were rainfall more evenly distributed through the year.

[5] Peat of a kind, or carbonaceous sediment, will be laid down in a semi-desert, in spite of slow plant growth, dry air, irregularity of precipitation, dust, and temperature favorable to rapid and complete decomposition, if the water conditions at the surface of the ground are sufficiently favorable. See the "tule" peats of California. In fact, water conditions determine whether there will ultimately be any peat anywhere.

the swamp, removing the suspended or dissolved decomposition products, some of which are toxic to the microbes themselves, or dilute the toxin-laden [6] waters so that they are no longer toxic, besides bringing fresh oxygen for the rejuvenation of the microbian action or, perhaps, even eroding the outlet to a lower level, so as to drain and expose the peat; (*d*) the vegetal supply or plant ingredient contribution, which is rarely too little if other conditions are sufficiently favorable, and which is best when grown in a warm humid environment,[7] where lush growth impedes circulation and run-off of the water itself, including the dissolved toxic products, and aids rapid upbuilding of the peat, while at the same time helping to restrict and smother decay by the more complete exclusion of atmospheric oxygen; [8] (*e*) the agents of disintegration and decomposition, including the *Actinomyces* at first and, particularly important throughout, the bacteria, especially the anærobic bacteria.

RELATIVE RESISTANCE OF PRINCIPAL PLANT COMPONENTS TO SUBAQUEOUS DECAY.

From the examination of plants decomposing under water and from the study of peats, it has long been known that in the process of decomposition certain parts, chemical compounds, of the plant disappear promptly and that others are relatively indestructible, while still others are characterized by intermediate degrees [9] of resistance to the microbian attacks. This differential resistance, which has been confirmed by the micro-study of debris petrified at different stages of decomposition, and of thin sections of coals, has been experimentally demonstrated in the laboratory,

[6] Water saline from salt springs or salty in consequence of advanced evaporation, is inimical to vascular land plant growth, though its saltiness impedes decomposition, and, if very pronounced, may arrest it.

[7] Simultaneously the warm humid environment promotes microbian activity.

[8] Lush growth, by obstructing the drainage, not only conserves the decomposition products, and so prevents waste of the ingredient material, thus building up the peat more rapidly, but also opposes the influx of extraneous inorganic matter and promotes greater purity of the deposit.

[9] Varying somewhat according to local conditions, such as kinds of vegetation, temperature, and water composition.

with control of the biochemical process, by Dr. S. A. Waksman,[10] who has chemically compared the partially decomposed debris with corresponding fresh material.

It is important at this point to recall that the general order in which the groups of related compounds in the plant parts or products are broken down and disappear in the process of peat formation is: (1) protoplasm; (2) chlorophyll; (3) oils; (4) the carbohydrates, including in sequence the starches, celluloses, and lignins, the latter being much more resistant than the others; (5) epidermis; (6) seed coats, with protective secretions; (7) some pigments; (8) cuticles, especially those with heavy protective cutins; (9) spore and pollen exines made very resistant by resinoid or waxy deposits; (10) waxes; and (11) resins. The last four named are exceedingly resistant and remain long after all the weakly resistant and nearly all of the moderately resistant have vanished.

The succulent plants and the succulent portions of land plants, being largely water and non-resistant material, are very perishable and of little value in the formation of banded coals. The most important ingredients in these coals are the carbohydrates—the vascular tissues, the woody parts, bast, cork, etc.—and the still more resistant though quantitatively much smaller parts and products. This is evident from the examination of the coals of all ages from the upper Devonian to the present day.

The chief groups of carbohydrates taking part in vascular plant structures as generally distinguished on a chemical basis are (*a*) the celluloses; (*b*) the hemicelluloses (including pentosanes, hexosanes, and uronic acids); and (*c*) the lignins. The conclusion that the latter are the most resistant of the series to subaqueous decay finds experimental as well as observational confirmation in the investigations by Waksman who, while showing that the relative rates of decay in these groups vary somewhat with the kinds of plants and the environments, presents evidence that the celluloses generally succumb sooner and more completely than the hemicelluloses.

[10] See Waksman, Selman A.: Die Rolle der Mikroörganismen bei der Torfbildung. Zeitschr. "Brennstoff-Chemie," Bd. 13, S. 241–247. Essen, 1932.

The fossil vascular floras have differed from age to age as to genera and species, but the writer can find no evidence that the principal peat-forming plant compounds—the starches, the other carbohydrate structures, the nitrogen compounds, the cutins, the gums, the spore and pollen exines, and the waxes and resins—of the later Paleozoic plants differed in general or in any important particular from those of the coal-forming vegetation grown in similar climates in the Mesozoic or the Tertiary. The chemical constitution of wood was then as now. Coals as such should be viewed not so much with reference to their Sigillarian, Taxodial, or Pteridospermic origin as with regard to their former contents of celluloses, hemicelluloses, lignins, etc. The processes by which plant decomposition was effected seem to have been essentially the same in the Paleozoic as now. Plant as well as animal diseases were prevalent in Carboniferous as well as later time, and bacterial activity, demonstrated in organic deposits of upper Paleozoic age, can alone explain the early decomposition of the plant organism and the resulting carbonaceous character of certain shales of pre-Cambrian age.

EFFECTS OF CHANGES IN LEVEL AND TOXICITY OF THE WATER.

The relative resistance to biochemical decomposition of the various plant parts of the organic debris contributed as ingredient material for the formation of peat is a factor of the most far-reaching importance. It accounts not only for much of the variation from layer to layer in the coal, but it is partly responsible for the " layering " of the deposit.

Not less important is the water factor, for, as has already been foreshadowed, the water conditions control the length to which microbian action is allowed to proceed. They determine whether decomposition is soon arrested, before all the parenchyma is destroyed and while all or nearly all of the woody tissue and bast remain; whether most or all of the pectins and celluloses also are lost, and whether the lignins, the most resistant of the carbohydrates, also are to go, leaving only the very resistant parts, and finally the most resistant, such as highly protected cuticles and exines and the nearly indestructible waxes and resins. In other

words, the state of the water and the consequent degree of its toxicity determine whether the entire great carbohydrate group, the most imposing and important contribution to the peat-forming surface, is in part or wholly to disappear—to be sacrificed, in fact —before and if ever toxicity sufficient to save remaining components is attained.

The effects of changes in the water conditions of the peat-forming area on the relative conservation from time to time of the organic debris, and the consequent differences from layer to layer in the kinds and amounts of the plant parts surviving and composing the layer as the toxicity of the water (content of plant decomposition products toxic to the ærobic and anærobic bacteria) fluctuates,[11] may be illustrated roughly with the aid of the accompanying graph, Fig. 1.

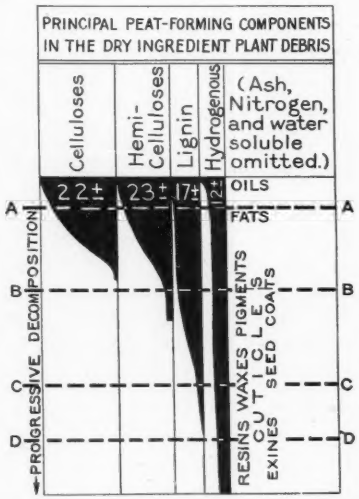

FIG. 1. Approximate proportions of principal peat-forming plant substances platted according to relative resistance to microbic decomposition, and order of disappearance.

[11] Fluctuations are mainly due to stagnation or evaporative concentration of the water, or to drainage, flushing, dilution, or wind oxidation which permit dissemination, removal, or decomposition of toxins.

In this diagram are rudely shown, by size of the dark blocks, the proportions of the main carbohydrate groups (celluloses, hemicelluloses, and lignins) and the hydrogenous aggregate (mainly ether-soluble) while the relative resistance of these components to bacterial decomposition—*i.e.*, the order of their disappearance if the microbian action continues long enough—is shown in the vertical direction.

These proportions are based on a rough estimation of the growth of vascular plants, including herbs and trees, on the average area of lowland peat swamp during a period of 60 years, the analyses by Waksman [12] of grasses, peat moss, hard wood, and cypress being used in the calculations. Though it may be misleading to call the latter "approximations," they suffice for the present purpose, since variations in the proportions and even in resistance do not affect importantly the general order of disappearance or the results indicated.

For a first case, let us assume that the peat-forming surface of a great forest-covered swamp comparable to the Great Dismal Swamp before it was drained, though generally very much more extensive, is at the time of our inspection very shallowly covered or nearly covered with water which is essentially stagnant [13] over most of the area, and which, as the result of the decomposition of debris already sacrificed, is fully toxic, or perhaps even slightly concentrated by evaporation due to a short dry season. The water medium being completely toxic to the destructive bacteria of all kinds at the level of sedimentation, decomposition of infalling refuse ceases as soon as the very small amounts of oxygen they are able to utilize, including that adhering to or carried down by the debris, is consumed.

Under these conditions very little of even the highly perishable tissues will be broken down in the immersed debris, and the preservation of the plant parts will be nearly complete, as is seen

[12] Waksman, Selman A.: *Op. cit.*, pp. 6 and 8.

[13] Dense vegetation very effectively retards the penetration by current infiltration of fresh supplies of water, as from rains, from the shore-lines and waterways into the interior of the swamp, and obstructs wind agitation; it is therefore important as promoting stagnation and the conservation of the toxic products of bacterial decay.

in the carbonate nodules, the so-called "coal balls," in which in some instances the structures of parts of the cambial layer, of pith, etc., are marvellously retained.[14] In this case we have the maximum survival of tissues, including celluloses, as well as the series of more resistant elements. Losses of the ingredient vegetation through biochemical decomposition are reduced to a minimum and the rate of peat building is as rapid as the plant supply, which depends mainly upon the climate, will permit.

Generally, however, the water cover is not fully toxic, and wind agitation of the cover introduces some oxygen from the air, so that decay proceeds until the toxicity of the water held stagnant in the matted debris under the protection of newly falling refuse is enriched to the degree prohibitive of further bacterial action, and biochemical decomposition is arrested.

A relatively early arrest of the bacterial action may be reached before all the cellulose is destroyed and while much of the hemicellulose group, most of the lignin, and practically all of the most resistant elements[15] remain. In this case, represented by cross section *A–A* of the graph (Fig. 1), the peat laid down in the tree-growing swamp will be conspicuously woody or xyloid and *generally,* if not universally, *brown.* In due time the wood and other tissues will become selectively impregnated by brown "humic" (or "ulmic") matters in the surrounding aqueous medium and not improbably really generated in part in the tissues themselves. The latter soften and later, under loading by superposed strata, collapse, with flattening of the cell cavities. Still later, in the course of the evolution of the deposit to coal of higher ranks, the deposit becomes progressively dehydrated and the humin-permeated fragments of wood, bast, etc., become black and lustrous, with glossy conchoidal fracture. In this state the shiny fragments of humified wood form the bright or "glance" strips, layers, stringers, and lenses termed *anthraxylon* by Thiessen. This appears to be indistinguishable from the *vitrain* (vitrite) of

[14] Decomposition may and in many cases did go further in layers containing "coal balls" after the carbonate replacement had occurred.

[15] The vegetable oils as well as some of the fats appear to break down at early stages.

Stopes and some other European students, and the thin bright xyloid bands in the "clarain" of some writers. The relatively high degree of conservation of the woody ingredients in anthraxylon layers marks rapid deposition and relative purity of the organic deposit.

At a stage roughly corresponding to *A–A* in the diagram, the highly hydrogenous debris of the column at the right, being comparatively small in amount, is diffused, mostly concealed, and of minor importance in the aggregate. If, however, due to conditions such as dilution of the toxic solution or replacement by fresh water, or aeration of the water, or temporary exposure of the peat, all of which are favorable to the further continuance of bacterial activity, more of the carbohydrates group—say all the celluloses and most of the hemicelluloses—are lost, a stage such, for example, as that indicated by cross section *B–B* of the graph, may be reached. Here thin strips and layers or lenses of humified woody residue are found embedded with fragments of cuticles and much other minute or micro-debris ("attritus"). If the layers of humified tissue (anthraxylon) are sufficiently thin and not too numerous, the peat, probably black, is destined to become *clarain*. Plainly, at this stage the hydrogenous spore exines, resins, etc., form a larger proportion of the organic residue than in vitrain, and the pure organic matter is likely to have higher calorific value.

Or, again, decay may have gone still further, so that, as indicated, for example, in the cross section *C–C*, all the celluloses and hemicelluloses [16] and most of the lignin structures may have disappeared, leaving but scanty residues of the latter as micro-debris along with the resistant cuticles, some of the highly protected seed coats, some pigments and waxes, and the exines and resins. The latter group—the resistant hydrogenous elements—may now form the dominant and conspicuous portion of the deposit. We now see a highly sporiferous layer in which the ligneous vestiges and the more resistant elements are enveloped in a colloidal humic paste containing much micro-debris, largely from cells wrecked and in process of destruction at time of ces-

[16] Uronic acids remaining from the hemicellulose group may continue for an undetermined time.

sation of biochemical action. Evidently, too, the waste of plant ingredients is very great and deposition is at an extremely slow rate, probably less than one-tenth the maximum.

The most resistant components remaining after the disappearance of the carbohydrate groups, the oils, the fats, the gums, and the less resistant of the seed coats, cuticles, and waxy products, are shown to have continued on for a long time in an environment apparently far from fully toxic, if they were water-covered. Consequently, in many environments they are residual—concentrated in effect—where all other vestiges of fibrous or woody land plants have vanished. However, though exceedingly resistant to subaqueous decomposition, most of the exines and the resistant cuticular fragments and resins seem to have yielded, if long exposed, to subaerial decay. They appear, accordingly, to be relatively rare on those bedding planes of the coal where the occurrence of films or thick mats of fusain (to be discussed later) offer unmistakable testimony of exposure for a time of the surface of peat formation.

Where, as in the sluggish waters of bayous, ponds and those portions of the peat swamp in which the water was too deep for the growth of subaerial vegetation, the supply of vascular plants was largely dependent upon drift, while at the same time the water was subject both to current replacement and wave action, the environment would be very favorable for continued bacterial action. Here we find the residual resins and the resistant waxes and cuticles mingled with innumerable exines brought by wind and water to form *canneloid deposits* and typical *cannels.*[17] With maintenance of the water cover and relative isolation from land sediments—an isolation doubtless due in part, at least, to a barrier of intervening vegetation—the sedimentation of the ponds was comparatively even, and the deposit, when solidified in the

[17] Canneloid layers may be spread over large areas of anthraxylon or clarain if the surface of peat formation be flooded or the water drained or flushed so as to restrict the toxic content of the cover, or if the water becomes so deep as to preclude subaerial plant growth for any considerable period. Subsequent lowering of the water and greater concentration of the biochemical products may permit resumption of deposition of other types of peat.

course of time, was destined to become conchoidal in fracture with little trace of lamination, especially when unweathered.[18]

If the area of open water was large, the proportional contribution of trees mingled with other vascular plants was in general correspondingly less and consequently the residual cuticular element and the resins and waxes were less, while the dominance of exines might become almost exclusive. At the same time algæ, especially colonies of the fatty one-celled gelatinous types, were due to make their appearance, and where the water body was favorable they might predominate in the organic debris. Thus a *cannel-boghead* was formed, or, as the algæ appeared in still larger proportions, a *boghead* or *alga coal.*

In the preceding discussion little mention has been made of one important component of banded coals—namely, *fusain* ("mother of coal," "mineral charcoal," "fusite"). It is readily seen to consist mainly of fragments of wood and other fibrous (carbohydrate) structures usually found spread on the bedding planes. In some coals layers with fusain are rare, especially if the coals are dominantly vitrainous, but in many beds fusain is very abundant, being scattered in thin, sometimes thick,[19] layers which carpet innumerable laminæ and which, by their weakness and friability, permit the coal to split easily along these layers, while at the same time providing much of the organic dust of the coal mine. In some regions and beds fusain sheets are so close one to another as to suggest that very many or even most, if not all, of the laminæ carry littered or very thinly sheeted fusain.

The origin of fusain is not yet fully proved. It is viewed by many geologists, engineers, and chemists as (*a*) charcoal products of forest fires on the upland or other areas bordering the swamp, from which it is washed or drifted, to be spread out by wind and water over the surface of the peat[20] formation; (*b*) remains from

[18] Lamination of cannels, almost never strongly marked, may in most instances be attributed to seasonal changes of temperature and in rate of sedimentation, rather than to temporary exposure.

[19] Thicknesses of one centimeter or more are comparatively rare, but instances of much greater thicknesses are known.

[20] This theory, harmonious with the theory of coal formation by driftage of the ingredient vegetation, now disproved for banded coals in general, is contradicted by several facts, among which mention may be made of (1) the incredible number and

forest fires burning in the surface strata of the peat during exposure of the latter through very dry periods,[21] and (*c*) as fragments of wood, bast, etc., in which, when already partly decomposed, some chemical change rendering them immune to further subaqueous bacterial decomposition, took place on exposure of the debris to the air by reduction of the water cover.[22]

Very common in fusain are fragments of wood from which the middle lamellæ and the original cell walls have been removed, the layers (lignin) thickening and lining the cells being now changed to fusain and apparently cemented by humic paste, now hardened from the biochemical decomposition material once in solution or suspension.

Fusain, even in scattered fragments, is scarce in canneloid deposits, rarer in conchoidal cannels, and very rare in bogheads. Stray pieces, probably slipped or drifted from the surface of the peat, may be found in the depressions, ponds, or lakes, but the larger these ponds are the more infrequently is fusain found, a condition diametrically opposed to the drift theory; for if charcoal was floated out from the old land, the bayous, oxbows, and lakes where the cannels are laid down should be filled with fusain. Even carbonaceous shales, unquestionably open water deposits, should be sheeted with it.

Whether the presence of fusain denotes fires in the peat surface or results from air drying at an early stage of decomposition, there is little doubt that the laminæ sprinkled or sheeted with its

closeness of the thin fusain spreads; (2) the extraordinary continuity and area of the sheets and their relative eveness; (3) the probable obstruction offered by the dense plant growth to the predicated widespread but diffused current movements.

[21] Against this view are (*a*) the lack of fire pits in the coal bed and the lack of inorganic ash deposits in those pits; (*b*) the relative evenness and great continuity of the fusain sheets; (*c*) the close proximity, less than a millimeter distant in many cases, of those sheets; (*d*) the orientation of the sheet material, often embracing large pieces of wood, the fragments of which are disposed in normal attitudes and only slightly separated; (*e*) the rapid transition from fusain to anthraxylon (vitrain) in the same layer and even in the same plant fragment; (*f*) the presence, on the laminæ, of fragile fern pinnæ and pinnules in which the most delicate nervilles are changed to fusain; and (*g*) the lack or great rarity at best, of similar sheets recognizable as charcoal in the present-day peats and in lignites.

[22] White, David, in Treatise on Sedimentation, by W. H. Twenhofel and collaborators (The Williams & Wilkins Co., Baltimore, Md.), 2d ed., p. 376, 1932.

fragments marked as many exposures of the surface of the peat. Countless fusain layers, seen in some coals, and seemingly, though probably not actually, as numerous as the laminæ themselves, and so close as to appear inseparable, give testimony of seasonal—presumably annual—reduction of the water level of the peat-forming surface.

In previous discussions I have pointed out that the laminæ, often very distinct in a bench or a whole coal bed, are climatic records, dominantly seasonal—varves, in effect. In these changes the principal factors are fluctuation (1) of the rainfall, which controls the water level; (2) of the temperature, which affects the rate of plant growth, the rate of decay, and the water level; and (3) of the toxicity, dependent on the level and the degree of stagnation of the water. Of these factors, which interact, the distribution of the rainfall and the temperature range through the year are doubtless dominant, either directly or indirectly, in those climatic fluctuations of which the laminæ of the coal are a consequence.

The term "durain" (durite) is applied to coal in layers consisting largely of resistant residual material including much micro-attritus, some of which is more or less distinctly opaque [23] when viewed in thin sections at high magnification. The explanation of the opacity, which is noted in layers in which some or even most of the constituents are not opaque, is yet to be demonstrated. Many students are disposed to explain it as due to the presence of certain kinds of plants, or rather, *plant products* not found in other coals, and cite the presence of a particular type or types of spore exine, reported to be characteristic of durain coal, in proof of this hypothesis.

The writer regrets finding himself unable as yet to accept this explanation for the following reasons:

(1) Durain has definitely been proved only in bituminous coals of fairly high rank. The British coals containing it range mostly between 61 and 64 per cent. fixed carbon, pure coal basis.

(2) The so-called "saddle-shaped spores" are not always present.

[23] "Opacity" is used relatively. Its degree depends upon the thinness of the sections.

(3) Opaque micro-debris is not always observed when the spores are abundant.

(4) The range in geologic age of the beds said to contain durain is greater than the vertical range of any one species of Paleozoic plants. On the other hand, if durain, reported to be abundant in the coal beds of certain regions, owes its opacity to a genus or group of plants, this opaque matter should be very widespread and not infrequent in coals of ages and regions where the group is abundant, regardless of the ranks of the coals.

(5) It is to be remembered that durain appears to have been found only in Paleozoic coals of ranks approaching if not already in the coking group. They are nearing the point where in the course of progressive regional carbonization most of the attrital matter of the coal turns dark—so dark, in fact, that it is not amenable to satisfactory examination under transmitted light.

To the writer it seems possible that in the reported durain coals we have to do with some components which darken sooner than other ingredients. This precocious darkening may be due to the presence of particular plant compounds, as suggested above, or to the conditions experienced by one or more compounds in the course of their deposition. Owing to the difficulty of examining the microsections of coals of the higher bituminous ranks, information as to the identity of the plant products which first become opaque, and as to the order and stages at which others develop opacity is almost entirely lacking. If the assumption that the opacity is due merely to the presence of a particular unidentified plant product is correct, we should find durain in relatively low rank coals whenever that particular plant is present.

On the other hand, before reaching a final conclusion as to the opacity in durain, we must know whether something corresponding to durain occurs in Mesozoic and early Tertiary coals when, in the course of their progressive evolution, they reach the same stage of carbonization.

CONCLUSIONS.

(1) In a forested swamp such as those in which banded coals were formed as peat, the proportions in which the principal "components" of the coal, (1) anthraxylon (vitrain), (2) fusain

(mineral charcoal), (3) clarain (attritus, durain), and (4) the very decay-resistant exines, resins, waxes, and specially protected cuticles, are deposited from time to time in the different layers depends on the state of the water into which the ingredient material falls—*i.e.*, on the water level, changes of the water, and the degree to which the toxic biochemical products of plant decomposition are conserved and concentrated in the aqueous solution.

(2) The coal may be distinctly *humic* when largely composed of " humified " woody matter, the *anthraxylon* or *vitrain;* it may be relatively high in fixed carbon when *fusain* is abundant, or it may be more fatty (*hydrogenous*) when nearly all of the plant matter is lost through biochemical action except the spore exines, resins, and waxes.

(3) All these components may each predominate from time to time, characterizing the layer, and this may take place without change in the kinds or the amount of vascular ingredient vegetation.

(4) The sheets of fusain carpeting the laminæ of the coal are interpreted as indicating exposures of the peat surface after deposition of the lamina and probably when partial humification of the woody debris, now composing each sheet, had taken place. When carpeting successive laminæ in great numbers, fusain probably represents seasonal exposure.

(5) The laminæ of banded coals are the records of periodic fluctuations in the environment, the dominant factors being seasonal variation in the rainfall and in the temperature.

(6) The rate of deposition of the coal-forming peat varies widely from time to time. The conservation of the ingredient vascular debris laid down in a thin water cover, in which the toxic decomposition products are fully concentrated—conditions of vitrain (anthraxylon) formation— may be over ten times as great as where, due to low toxicity of the water, or long exposures to the air, only the most decay-resistant plant residues are left.

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THE ORIGIN OF THE ASPHALT DEPOSITS OF WESTERN KENTUCKY.

WILLIAM L. RUSSELL.

INTRODUCTION.

THE asphalt deposits of western Kentucky are the most productive in the United States. They are found on the southeastern edge of the Eastern Interior Coal Basin, and down the dip under cover, oil and gas are found in the same general horizons that contain asphalt at the surface. Since the asphalt deposits appear to be former oil pools that have been altered by superficial agencies, it is evident that the origin of oil and asphalt must be the same, and that any conclusions as to the origin of asphalt would have an equal bearing on the origin of oil. The chief purpose of this paper is to solve the most important problem regarding the origin of the asphalt deposits: whether they came up from some deep seated source or were generated in the closely associated rocks. If the oil from which the deposits were developed came from a formation far below, this fact should have an important influence on the theories of migration of oil in this and similar regions, whereas if it originated in contiguous strata it should be possible to find these rocks at the surface and thus determine, for this case at least, the nature of the source rocks of oil.

The information on which this paper is based was secured by the writer during the course of a number of years' geological work in western Kentucky. Many of the data were gathered while employed by the Cumberland Petroleum Co. in 1932 and 1933.

STRATIGRAPHY.

The stratigraphy of the region in which the asphalt deposits occur is summarized in Table I. The formations are also shown in section in Fig. 2. The formations in the Chester Series, although persistent over great areas, are highly variable in their

characteristics from place to place. The limestones below the Leitchfield formation are the most uniform members of the series, but even these are in places partly replaced by shales. The names given to the subdivisions of the Chester Series below the Vienna limestone suggest that they are composed entirely of limestone and sandstone. This is far from being the case, for all the sandstones are locally replaced by shales. The Cypress is more persistent and uniform than the other sandstone members, but even in the asphalt area it varies from a massive sandstone 60 feet thick to a series of shales with only a few feet of sandstone. The Pennsylvanian strata are also highly lenticular and variable.

A feature of the stratigraphy that has had an important influence on the formation of the asphalt deposits is the marked unconformity at the base of the Pennsylvanian. The basal Pennsylvanian strata were deposited on a surface with a local relief of 200 feet or more, and in northern Edmondson County and adjacent territory to the west there are a series of deep valleys filled with Caseyville sandstone containing asphalt deposits in places.

Some of the stratigraphic and structural data in this paper have been taken from the publications of the Kentucky State Geological Survey.

REGIONAL STRUCTURE.

The main structural feature of the region is of course the Eastern Interior Coal Basin. The regional dip of the strata is in general towards the northwest into this basin at a rate that varies greatly, but is for the most part around 20 to 30 feet per mile. Another important feature is the Rough Creek Uplift (Fig. 1). It extends in an east-west direction, but dies out in the eastern part of the asphalt area. South of the Rough Creek Uplift is the Moorman syncline, which also extends in an east-west direction. South of the Moorman syncline there are two broad, gentle anticlines and corresponding synclines. One of these broad, flat anticlinal noses extends in a west-northwesterly direction from the Bowling Green oil pool in Warren County, and

TABLE I.

LIST OF FORMATIONS PRESENT IN THE ASPHALT REGION.

Pennsylvanian	Tradewater	Shales and sandstones	
	Caseyville	Sandstone, conglomerate and shale, with important asphalt deposits, 50 to 300 feet thick	
Mississippian: Chester Series	Kinkaid limestone	Hard, gray crystalline to dense limestone, 0 to 60 feet thick, but generally absent	
	Leitchfield formation	Greenish shales, with occasional beds of pinkish shale and thin limestones, thickness 0 to 300 feet	To the west the Menard and Clore limestones and the Waltersburg, Palestine and Degonia sandstones replace most of the Leitchfield shales
	Vienna limestone	Hard, very persistent limestone, 5 to 20 feet thick	
	Tar Springs sandstone	Lenticular sandstone and shale, 35 to 60 feet thick	
	Glen Dean limestone	Light to dark gray limestone with some interbedded shale, 50 to 75 feet thick	
	Hardinsburg sandstone	Sandstone, in places lenticular, and bluish-gray shale, 20 to 50 feet thick	
	Golconda limestone	Crystalline limestone, 25 to 50 feet thick	
	Cypress sandstone	Persistent sandstone, in places interbedded with, or underlain and overlain by, shale. The formation is 10 to 70 feet thick and contains important asphalt deposits	
	Paint Creek limestone	Grayish, crystalline to dense and oölitic limestone with some shale, 20 to 60 feet thick	
	Bethel sandstone	Sandstone and shale, 0 to 50 feet thick, present only on the north	
	Renault limestone	Grayish limestone, crystalline, dense and oölitic, 15 to 80 feet thick	
	Aux Vases (?) sandstone	Sandstone and shale, 0 to 20 feet thick, present only on the north	
Mississippian: Iowan Series, Meramec Group	St. Genevieve limestone	Light colored limestone, crystalline, dense and oölitic, about 180 feet thick	
	St. Louis limestone	Light colored to nearly black limestone, fine grained to dense, about 300 feet thick	
Mississippian: Iowan Series, Osage Group	Osage	Limestone, shaly limestones, and shales, mostly calcareous or silty, about 500 feet thick	
Devonian or Mississippian	Chattanooga shale	Hard, dark brown to black, richly bituminous shale, 60 to 150 feet thick	

the other extends from eastern Edmondson County west-northwest into Grayson County, where it dies out. Each of these anticlines is flanked on both sides by a corresponding syncline. The variations in the interval between the Cypress sandstone and

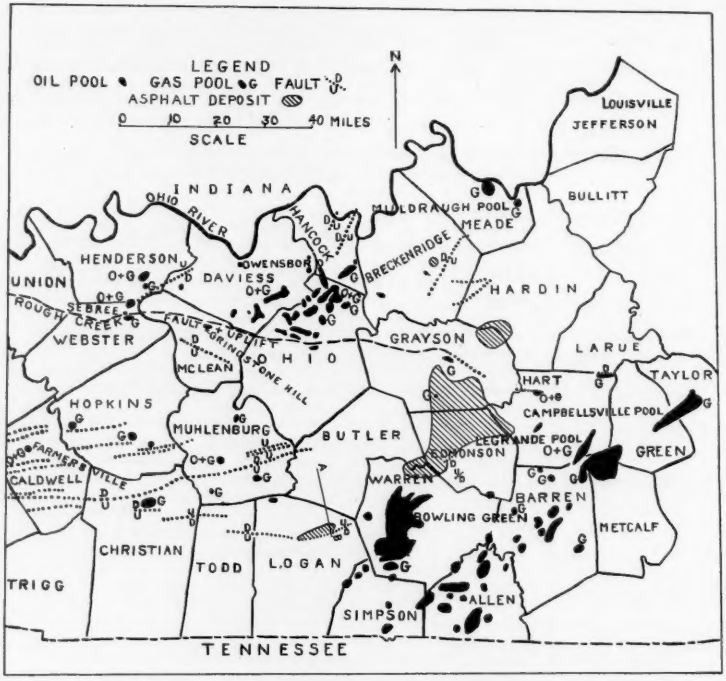

FIG. 1. Map of asphalt deposits and oil and gas pools of western Kentucky.

the Chattanooga shale indicate that the Eastern Interior Coal Basin, the Rough Creek Uplift, and the Bowling Green Anticline were all forming during Mississippian time, though most of the folding took place after the deposition of the Pennsylvanian.

THE ASPHALT DEPOSITS.

Distribution.—The areal distribution of the asphalt deposits and their relation to the oil and gas pools are shown in Fig. 1. The thickness of the asphalt varies so irregularly that it would be impossible to show the individual deposits accurately on a map of this scale, even if their locations were accurately known. Actually showings of asphalt occur scattered through the Chester sandstones along their belt of outcrop from the Ohio River to Logan County. It is often difficult or impossible to determine without core drilling or excavation whether an outcrop of asphaltic sandstone is a local patch or an important deposit. The shaded portions of Fig. 1 indicate areas in which the scattered asphalt deposits are unusually abundant. There are parts of these shaded areas that contain no asphalt, and there are many scattered deposits that are not shown.

Although showings of asphalt may occur in any of the sandstones of the Chester and Lower Pennsylvanian present in the asphalt region, nearly all the important deposits are in the basal Pennsylvanian sandstone and in the Cypress sandstone. In the large shaded area in and adjacent to northern Edmondson County most of the asphalt is in the Pennsylvanian, and in the other areas most of it is in the Cypress sandstone.

Relation of Asphalt to Oil Pools.—The relation between the areal distribution of the oil pools and asphalt deposits is shown in Fig. 1. The oil and gas pools east and southeast of the asphalt deposits are in Silurian, Devonian, and lower Mississippian limestones and dolomites, but the oil and gas pools west and northwest of the asphalt deposits are all in Chester and Pennsylvanian sandstones, with the exception of the oil pool south of the Rough Creek Uplift in Ohio County. Although the most important asphalt deposits are in the Pennsylvanian, most of the oil production comes from the Chester. The most important asphalt deposits of the Chester are in the Cypress sandstone, but most of the oil production from the Chester comes from the Tar Springs, Hardinsburg, Bethel and Aux Vases (?) sandstones, and the Cypress has produced only minor amounts of oil.

Alteration of the Oil Pools to Asphalt.—Wells drilled down the dip from the outcrops of asphalt in the Cypress sandstone reveal a significant relationship between the asphalt and the oil showings in the same sandstone. Where the Cypress is found at shallow depths, such as 50 to 300 feet below drainage level, it is reported to contain fresh or brackish water in the lower portion of the sandstone, and asphalt or heavy oil in the upper part. This relationship suggests that the oil in the Cypress was altered by the circulation of ground water before it reached the surface, as the covering rocks were removed by erosion. Presumably the oil combines with the oxygen in solution in the ground water, and the lighter constituents of the oil, which are slightly soluble in fresh water, are dissolved and carried away. No doubt the final stages in the formation of the asphalt are completed when the material is exposed to the air.

If the asphalt deposits have been formed by the circulation of ground water, it is to be expected that the asphalt deposits would be most common where the ground water circulation is most active. In general this appears to be the case. The sandstone in the Chester that contains most asphalt is the Cypress, which is the most persistent. Although the Caseyville sandstones at the base of the Pennsylvanian are individually rather lenticular, there is so much sandstone at this horizon that water may be able to circulate from one sandstone to another. In the southwestern portion of the Western Kentucky Coal Basin, where the sandstones may be less persistent and permeable, and where, as is indicated by Fig. 1, they are cut by many faults, there is little or no asphalt.

The movement of ground water postulated is from an outcrop at high elevation to one at lower levels in a neighboring river valley. There is probably no artesian circulation from one side of the basin to the other.

DERIVATION OF ASPHALT DEPOSITS FROM THE CHATTANOOGA SHALE.

Permeability of the Intervening Rocks.—In his description of the asphalt deposits of Edmondson county, Weller [1] states that the oil from which the asphalt was formed probably originated in the Chattanooga shale. In order to test the validity of this theory it is necessary to consider the character of the intervening rocks. In their outcrop east of the asphalt region the strata of Osage age, which lie just above the Chattanooga shale, consist of shales and limy shales, with numerous beds of limestone, especially near the top, and intercalated silty calcareous shales. Towards the west the shales become limy or change to limestones under cover, but even in the asphalt region there is a considerable thickness of limy shale. Beds of greenish shale are generally present close above the Chattanooga shale. Because of their shaly character the Osage strata appear to be rather impermeable. Between the top of the Osage and the base of the Chester the rocks are almost entirely limestone. Most of this limestone is without porosity, except possibly where fractured, but there are two general horizons at which the limestone is locally highly porous. One of these horizons is several hundred feet above the top of the Chattanooga shale and near the base of the St. Louis limestone, and the other is in the St. Genevieve limestone or uppermost St. Louis, about 100 to 300 feet below the base of the Chester. On the southeast side of the basin some wells go from the base of the Cypress sandstone to the top of the Chattanooga shale without finding water, but many of them find one or more flows of water at the two horizons mentioned.

Additional evidence bearing on the permeability of the limestones is given by the shallow production in the Bowling Green oil pool, Warren county. In this section considerable oil and gas have been found in a limestone or dolomite several hundred feet above the Chattanooga shale and four or five hundred feet below the surface. This is in the lower of the two porous hori-

[1] Weller, J. M.: Geology of Edmondson County. Kentucky Geol. Survey, Ser. 6, vol. 28, p. 206, 1927.

zons in the Mississippian limestones. Although the rocks between the surface and the soil are all limestone, there were no oil and gas seeps in the pool before production was found, as far as could be ascertained. This evidently indicates that these limestones are not permeable at present.

Relation of the Oil, Gas and Asphalt to the Chattanooga Shale.—In a previous paper the writer [2] has cited evidence to show that the oil found in the Chester sandstones of western Kentucky originated in the closely associated formations, and did not rise from the Chattanooga shale. Additional evidence is furnished by the asphalt region. If great volumes of oil have ascended from the Chattanooga shale, one would expect that the porous strata closer to the Chattanooga shale would contain considerable oil. This, however, is far from being the case. The porous horizon in or near the St. Genevieve limestone is generally devoid of important oil accumulations in this region, though it has produced a little oil in Muhlenburg county to the west. The lower porous horizon in the Mississippian limestones has produced oil in several areas, but in some places in the asphalt area it is devoid of oil, even on closed surface structures.

More striking evidence is furnished by the relations of the oil and gas to one another. If the oil and gas came up from the Chattanooga shale, it is to be expected that the gas, being lighter and more motile than the oil, would migrate upward more readily, and that the oil would become relatively more abundant towards the Chattanooga shale, with gas present in comparatively greater amounts in the upper strata. The true relations, however, are exactly the opposite. In the Chattanooga shale itself, small flows of gas have been found in many wells, while oil showings are absent or very rare. In the asphalt region and just southeast of it, many wells produce gas from a limestone or dolomite called the "Black Lime" or "Beaver Sand," which lies close above the Chattanooga shale. The production from this sand has been almost entirely gas. The overlying strata up to the base of the Pennsylvanian produce much oil as well as gas.

[2] Russell, William L.: Geology of Oil and Gas Fields of Western Kentucky. Amer. Assoc. Petr. Geol., Bull. 16, No. 3, pp. 248–250, March 1932.

Structural Relations of the Deposits.—The asphalt deposits do not appear to show much relation to the regional structural features of the region. The largest deposits occur in the eastern part of the Moorman syncline. In this portion of the syncline the strata dip gently towards the west and into the syncline without marked structural disturbances, though a few faults may be present. The Bowling Green anticlinal nose does not seem to have exerted much influence on the accumulation of the asphalt, although it has probably been a factor in producing the accumulation of the oil below the Chattanooga shale.

If the oil from which the asphalt was produced has ascended through faults, the deposits should show a tendency to be concentrated along them. If, on the other hand, the oil originated in the associated strata, the asphalt might also be concentrated along faults, but only where a fault produces a structural trap such as commonly produces an accumulation of oil.

The latter condition is found to be the rule in the asphalt region. Although most of the asphalt is not markedly related to the structural features, there are some accumulations in structural traps. In the northern part of the anticline extending north from eastern Edmondson county asphalt is more plentiful on the anticline and down the dip to the west than in the syncline on the east. Weller [3] states that asphalt is more abundant on the northwest side of the fault (Fig. 1) in west-central Edmondson County than on the opposite downthrown side. A small outcrop of asphalt occurs near a large fault on the uplift south of Beech Grove, McLean County. The most marked relation between an asphalt deposit and a fault is in northeastern Logan County, where the asphalt is found in a belt along the north or upthrown side of the fault and is comparatively rare on the other side. The relations between the asphalt deposit and this fault are brought out in Fig. 1, and in Fig. 2, which is a section at right angles to the fault. As is indicated in Fig. 2, the asphalt extends down the dip a considerable distance from the fault. A well drilled about seven miles north and down the dip from the fault is re-

[3] Weller, J. M.: *Op. cit.*, p. 207.

ported to have found asphalt or very heavy oil in the top of the Cypress sandstone, and still further down the dip to the northwest and west, oil and gas of normal gravity have been found in it. The asphalt along this fault occurs on the down dip side of a structure with 50 or 60 feet of closure. The fact that the asphalt is found just where an oil pool would be expected to be, and the fact that it extends far down the dip, apparently indicate that the oil from which the asphalt was formed did not issue through the fault, but migrated through the sandstone up the dip.

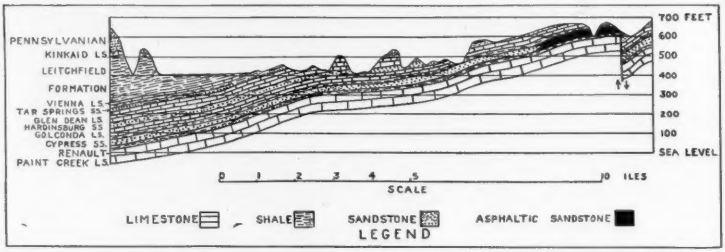

FIG. 2. Section from *A* to *B* in Fig. 1, showing the relation between the fault and the asphalt deposit in northeastern Logan County.

The limestones along faults and in areas of sharp folding are traversed by many fractures. At present these fractures appear to be tightly closed by calcite, though it is possible that before the deposition of the calcite they were open. In some places occurrences of fresh or brackish water far below the drainage level suggest that the faults may still be sufficiently open to permit fluids to migrate through them. A well drilled on the upthrown side of the fault shown in Fig. 2 near the point where the section crosses it, found fresh water containing hydrogen sulphide nearly 400 feet below the drainage level, and a well near the large fault south of Beech Grove, McLean County, found brackish water in the lower Chester sandstones about 800 feet below drainage level. Veins of fluorite, which must have come up from great depths, occur along the numerous faults on the southwest side of the Western Kentucky Coal Field, but there are no extensive asphalt

deposits near these faults. Although the faults may have been at one time sufficiently open for the oil and gas to migrate up through them, the field relations suggest that this migration did not take place on an extensive scale.

Migration of the Oil from Which the Asphalt was Formed.—The relation of the asphalt deposits to the faults indicates that there has been some migration of the oil from which it was formed. On the other hand, the occurrences of asphalt in the synclines, and the lack of relation of the deposits to the regional structures, suggest that this migration was generally limited. Judging by these factors, it may be estimated that the oil from which the asphalt was formed moved up the dip in many cases a few miles, but generally less than fifteen miles.

Volume of the Asphalt.—In order to obtain an idea of the thickness of source rocks necessary to form the asphalt, it is necessary to make an estimate as to the average thickness of the asphaltic sandstone. Owing to the extreme variability of the deposits and to the lack of information as to their extent under cover, this is difficult. However, a rough estimate may be made that if the asphaltic sandstone removed by erosion during the formation of the valleys which cut through the deposit were replaced, the average thickness of the deposit in the shaded areas of Fig. 1 would be about five feet. If the average asphalt content of the asphaltic sandstones was 5 per cent., this would make a layer of solid asphalt 0.25 feet thick. The fact that there are a number of seeps of tar in the region indicates that the volume of asphalt in the deposit is gradually diminishing even at present, and it is probable that some of the oil in the oil pools from which the deposits were formed escaped to the surface before it was altered to asphalt in the sandstone. Since the lighter constituents of the oil that did form the asphalt have also escaped, it is probable that the thickness of a layer of oil necessary to form a layer of solid asphalt 0.25 feet thick would be at least one foot. This thickness over the entire asphalt region would amount to about one billion barrels, and if, as is probable, during the accumulation of the oil pools some of the oil escaped up the dip without being trapped, the original volume of oil produced must have been even greater.

THE ORGANIC CONTENT OF THE ASSOCIATED ROCKS.

In discussing the origin of the asphalt deposits, Weller [4] says: "No beds are known either in the Pottsville of this region or in the underlying upper Mississippian formations which could have produced the vast amount of petroleum which the asphaltic horizons at one time contained." However, if this oil did not originate in the Chattanooga shale it must have formed in one or more of the formations between the Chattanooga shale and the surface. It seems reasonable to expect that a rock in which such large volumes of oil had been generated would still contain enough organic matter to be detected by testing samples of it in a closed tube. With this idea in view, the writer distilled in the closed tube a number of samples from all the formations between the Chattanooga shale and the top of the Caseyville formation in the Pennsylvanian. The rocks of the Osage group and the basal St. Louis limestone contain considerable organic matter. Some of these strata yield in the closed tube visible oil, an odor of oil, or other odors indicative of organic materials. Although some thin beds of limy shale near the base of the St. Louis contain so much oil that they will burn, most of the Osage and lower St. Louis beds yield far less oil than the Chattanooga shale. However, as they are much thicker than the Chattanooga shale, the total volume of organic matter in them may be nearly as great as that in the Chattanooga shale. The extensive series of limestones between the middle of the St. Louis and the lowest sandstone in the Chester are light colored and in general contain little bituminous matter, although the odors given by some of these strata on distillation indicate that in places they carry some organic material.

The Renault and Paint Creek limestones, which are for the most part light colored, generally yield no oil on distillation, though portions of them give various odors indicative of organic matter. In the northern part of the region, however, there is considerable shale between these limestones. This shale in places yields ammonia on distillation, and a little of it gives traces of oil or an oily odor. The sandstone associated with this shale is the

[4] Weller, J. M.: *Op. cit.*, p. 206.

Bethel sandstone (Barlow Sand of oil operators). A short distance down the dip it produces considerable oil. The shale associated with the Cypress sandstone, which contains the largest asphalt deposits in the Chester, is remarkable in that a considerable portion of it generates ammonia on distillation. Although some of the samples of this shale yield an odor of oil or traces of oil, only a small part of it is strictly bituminous. Some dark limestones in the upper part of the Glen Dean limestone give oil on distillation, but in general neither the Golconda nor the Glen Dean limestones show oil in the closed tube. However, many of these limestones give an odor of scorching or a white sublimate (probably ammonium sulphate) which indicates that small quantities of organic matter are scattered through them. Some of the shale associated with the Tar Springs sandstone produces ammonia on distillation, and some of the limestone in, or associated with, the Vienna limestone, emits oil or an odor of oil. A large portion of the Leitchfield shales, with which the most important asphalt deposits are closely associated, furnish ammonia on distillation. Some of the thin limestones in the formation generate a little oil on distillation, but the total volume of bituminous rocks in the formation is small compared to the volume of the shales yielding ammonia. The Caseyville formation, in which most of the asphalt occurs, consists largely of sandstone, conglomerate and sandy shale, though in some places it contains considerable shale. Some of the shales in or above this formation yield ammonia, but the total volume of these ammoniacal shales in this formation is much less than the volume in the underlying Leitchfield. There are some local deposits of cannel coal and very rich oil shale in the Caseyville, but these strata are of small extent, and the total volume of bituminous rocks in this formation is generally small. However, the characteristics of the rocks at this horizon are highly variable, and it is possible that there are limited areas in which these deposits are rich in organic matter.

THE SOURCE ROCKS OF THE ASPHALT.

It is natural to suppose that strata now yielding oil on distillation have been the source of the oil from which the asphalt was

formed. Because of the difficulty of migration of fluids across the strata, the most effective position of a source rock is in the formations closely associated with the sandstone in which the asphalt occurs. There are in places in the Chester or Caseyville formations beds of bituminous shale that are fairly thick, but in general the bituminous rocks in the Chester and lower Pennsylvanian are either thin or of small extent. Although it is difficult to obtain an accurate conception of the bituminous content of such variable formations from a limited number of samples, the available data give the impression that there is not in the associated Pennsylvanian and Chester formations a sufficient thickness of bituminous rocks to serve as a source for such large volumes of oil as must have been formed.

The Osage and lower St. Louis strata probably contain enough bituminous matter to serve as a source for the oil, provided it could be concentrated in the sandstones that contain the asphalt. Oil produced in the St. Louis and upper Osage would not need to traverse any shales to reach the Chester sandstones, as the shaly strata are chiefly in the lower Osage. If the oil that formed the asphalt really came up from below the Chester, these Osage and St. Louis rocks are the most likely sources. However, there is doubt about the permeability of the intervening rocks, and the lack of relation between the asphalt deposits and faults, together with the occurrences of water without oil in the porous portions of the St. Genevieve limestone, suggest that the source was in a higher horizon.

The asphalt deposits occur in sandstones that are closely associated with shales yielding ammonia on distillation, and the field relations suggest that these strata were the source rocks of the oil. The ammoniacal shales in contact with the Cypress sandstone are not thick, but, as this sandstone is persistent and the deposits of asphalt in it are scattered, the oil could be concentrated by migrating up the dip until it was stopped by stratigraphic or structural traps. The asphalt deposits in the Pennsylvanian are found in an area where the basal sandstone in which the deposits occur fills a series of rather deep valleys excavated in the Chester. This

brings the sandstone in contact with the whole of the Leitchfield formation, in which the extensive deposits of ammoniacal shales are found. As noted by Weller,[5] the asphalt occurs in the sandstone member of the Caseyville that is in contact with the Chester. Because of the large unconformity at the base of the Pennsylvanian, the position of this basal sandstone in the Pennsylvanian varies from place to place.

To the west of the asphalt region the Leitchfield shales are largely replaced by limestones and sandstones and the volume of the shales yielding ammonia is correspondingly reduced. Moreover, in this area the basal Pennsylvanian strata generally rest on higher members of the Chester than in the section where the deposits occur. In this region to the west, the Pennsylvanian is practically devoid of asphalt, and the basal sandstone does not produce oil down the dip. In northern Ohio County, oil is produced from a basal Pennsylvanian sandstone that occupies a similar deep channel in the Pennsylvanian, as the writer[6] has described elsewhere. It is of course possible that some oil may have entered the basal Pennsylvanian sandstones from the Chester sandstones with which they are in contact in the deeper channels.

Rocks yielding ammonia on distillation do not at first sight appear to be likely source rocks for oil. It is difficult to imagine oil forming in a rock which now contains no detectable traces of oil. However, the field relations, as far as they are known, support the theory that these shales which give ammonia on distillation have been the source of the oil from which the asphalt came.

CONCLUSIONS.

1. Some of the asphalt deposits have accumulated along faults where they form structural traps for oil moving up the dip, but in general the deposits are not related to faults.

2. The oil from which the asphalt was derived probably did not come from the Chattanooga shale.

3. The oil which formed the asphalt in some cases moved a few

[5] Weller, J. M.: *Op. cit.*, p. 201.

[6] Russell, William L.: *Op. cit.*, p. 250.

miles up the dip, but its movement was generally less than fifteen miles.

4. The field relations suggest that the oil from which the asphalt was produced was generated from shales in the Chester series that yield ammonia on distillation, though Osage, lower St. Louis and Chester bituminous rocks may be considered possible sources.

NEW HAVEN, CONN.

THE THUNDER MOUNTAIN MINING DISTRICT, VALLEY COUNTY, IDAHO.[1]

CLYDE P. ROSS.

FOREWORD.

THE Thunder Mountain mining district is in eastern Valley County, Idaho. It is of undefined extent but nearly all the development is confined to the ridge between Monumental and Marble creeks in unsurveyed T. 19 N., R. 11 E. (Fig. 1). The district is still remembered among the mining men of Idaho because of the ill-advised rush there in 1902, but available evidence indicates that optimism regarding the future development of the gold deposits of the district is warranted. The former disappointment arose from the fact that many who took part in the early rush hoped for bonanza deposits, whereas the district is characterized by large masses of low tenor.

In 1926 the writer, assisted by C. H. Behre, Jr., devoted four days to the detailed examination of the workings then accessible in the Sunnyside, Venable, Standard and H–Y mines, most of which were still in good shape; only surface exposures at the Dewey were studied, as the main workings there have long been caved. The time available did not permit more than a cursory examination of the surface at a distance from the mines. Sufficient data have, however, been gathered from published and unpublished accounts, production records and mine maps so that the major features of this deposit can be summarized. The kindness of Messrs. Dan McRae and R. A. Davis in making available information regarding these mines, and of these men and others in recounting early history and their observations in now-inaccessible workings, have aided materially in preparing the present

[1] Published by permission of the Director, U. S. Geological Survey, and the Secretary, Idaho Bur. of Mines and Geology. Presented at the Annual Meeting of the Amer. Inst. of Mining and Metallurgical Engineers, Feb., 1933.

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paper. A brief summary of the salient characteristics of the district has already been published.[2] Circumstances have contributed to delay in the publication of the full official report, which will contain mine maps and such other detailed data as could be obtained. In view of the present interest in gold deposits, it seems desirable to present here the major results of the study.

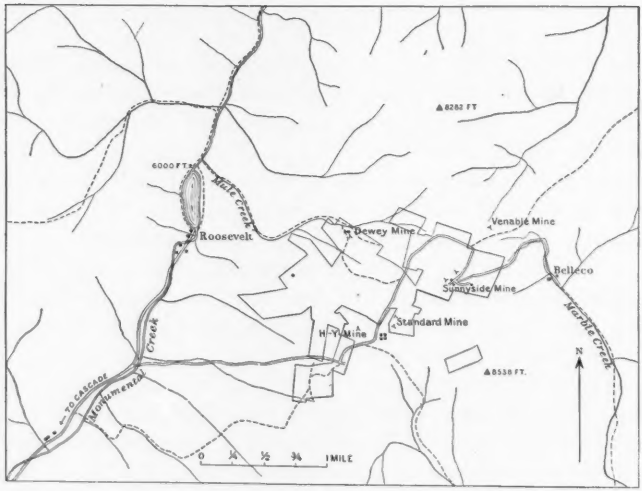

FIG. 1. Sketch map of Thunder Mt. Mining District. Modified from Forest Service data. Outlines of principal groups of claims from a map by G. C. Smith.

Historical Summary.—The discovery of mineral in the Thunder Mountain district was made by the three Caswell brothers and Huntley in 1895. They sluiced the soft material on the surface of the deposit in which the Dewey mine was later developed, and are reported to have made $6,000 to $7,000 each summer in this way. Their claims were purchased in 1901 by the Thunder Mountain Gold and Silver Mining and Milling Company, which

[2] Ross, C. P.: Ore Deposits in Tertiary Lava in the Salmon River Mountains, Idaho. Idaho Bur. Mines and Geol., Pamph. 25, pp. 2, 4, 9, 12–17, 1927.

promptly shipped in a 10-stamp mill and commenced underground development. Exaggerated accounts of the new gold district were widely circulated and resulted in a rush to it, of between 2000 and 3000 people,[3] in 1902. The towns of Roosevelt and Belleco sprang up, and claims were staked and prospect holes dug, many apparently at random, over an area of about 20 square miles. Present development indicates that most of the mineralization is confined to an area of 5 or 6 square miles. At a few places, such as the Sunnyside, H–Y, Standard, and Venable mines, considerable underground development work was done, but by far the most encouraging results were obtained at the Dewey, the original discovery. The period of active production was brought to a close about 1908.

From the incomplete information available,[4] it appears that the total production prior to 1901 was roughly $40,000. From then through 1908 the Sunnyside produced about $5,000 and the Dewey not over $350,000. Although a number of other properties were worked during this period, little production was obtained from them. Since 1908 it appears that little more than $20,000 has been produced in the district.

The remarkable landslide in May, 1909, completed the discouragement of most of the miners. It started close to the Dewey mine, moved over 2 miles down Mule Creek, and dammed Monumental Creek, flooding the town of Roosevelt. The lake thus formed remains today, although it is filling with silt. Subsequent activity in the district was confined to intermittent operations. The dumps of the Dewey mine have been largely reworked by placer methods, and small stringers and pockets of gold close to the surface have occasionally rewarded their discoverers. The neighboring streams have been prospected from time to time for placer gold, but the production from this source has not been encouraging. For some years prior to the writer's visit in 1926 a

[3] Bell, R. N.: Facts about Thunder Mountain. Eng. and Min. Jour., vol. 74, pp. 273–275, Aug. 30, 1902.

[4] Umpleby, J. B. and Livingston, D. C.: A Reconnaissance in South-central Idaho. Idaho Bur. Mines and Geol. Bull. 3, p. 6, 1920. Annual volumes of Mineral Resources of the United States, and the files of the U. S. Bur. of Mines.

10-stamp mill had been operated during the summer on ore obtained by a small force engaged in development work at the Sunnyside mine. It is understood that this limited operation has continued up to the present time. Notices in the press record the fact that the district has recently received some attention from mining scouts, but no increase in activity appears to have resulted as yet.

Access.—One of the major disadvantages of the Thunder Mountain district heretofore has been its remoteness from routes of travel. It is an extremely rugged region and until recently was over 70 miles from the railroad at Cascade by a road much of which was impassable to automobiles even in the short season when the high passes were free from snow. In recent years a modern road has been extended to a point within 15 miles of the district and the difficulties of winter travel have been in part overcome by the establishment of airplane service during this part of the year between the same point and Cascade.

GENERAL GEOLOGY.

The entire district and the surrounding region is underlain by the Challis volcanics, a thick sequence of lava flows and pyroclastics of early Miocene or late Oligocene age [5] which rests on an irregular surface of older rocks, some of which are exposed along Monumental Creek about 7 miles above, and 8 miles below Roosevelt. No Tertiary intrusive rocks are known in the vicinity of the mines, but there is a large intrusion of Miocene granitic rock [6] along the Middle Fork of the Salmon River about 11 miles to the east, and related dike rocks are plentiful on Rush Creek about 8 miles to the north.

The Challis volcanics in the Thunder Mountain district are preponderantly rhyolitic. The latitic and andesitic rocks that make up most of the lower part of the formation in other parts

[5] Ross, C. P.: Geology and Ore Deposits of the Seafoam, Alder Creek, Little Smoky, and Willow Creek Mining Districts, Custer and Camas Counties, Idaho. Idaho Bur. Mines and Geol., Pamph. 33, p. 2, March, 1930; Geology and Ore Deposits of the Casto Quadrangle, Idaho. U. S. Geol. Survey Bull. (in preparation).

[6] Ross, C. P.: Mesozoic and Tertiary Granitic Rocks in Idaho. Jour. Geol., vol. 36, no. 8, pp. 682–686, 692–693, 1928.

of south-central Idaho are not exposed here. The lower part of the sequence on the Monumental Creek slope is massive dark purplish rhyolite several hundred feet thick. Resting on this are light colored beds of rhyolitic lava, tuff, and conglomerate that include those containing the mine workings. The lava flows make up a small proportion of the total, and some of them are only a few inches thick. The total thickness of the light colored beds is 500 feet or more. The upper 200 feet of this is largely tuffaceous conglomerate with well rounded pebbles 1 to 2 inches in diameter, mainly of light colored rhyolite porphyry. Both the lava and the tuff contain pieces of silicified wood and other fragmentary plant remains. Some of the less silicified fragments are black and look charred. In places there are layers of impure lignite from a few inches up to as much as 2 feet thick. Large logs were found in the Dewey workings, and some of these contained much free gold.[7] About 200 feet of dense black basalt, in part vesicular, overlies the light colored beds at the Dewey mine and similar rock crops out in several other places on the Monumental Creek slope of Thunder Mountain. Although most of the light colored rock in the district is more or less hydrothermally altered, the basalt is nowhere known to be appreciably affected.

On the Marble Creek slope, where the Sunnyside mine is the only development of consequence, the geology differs in detail. On the lower part of this slope light pinkish and purplish lava with numerous quartz phenocrysts predominates over a vertical range of more than 1000 feet, with cream-colored tuff abundant below this. At higher levels, in the vicinity of the Sunnyside mine, there is light colored rhyolitic tuff and lava similar to that on Monumental Creek. No basalt, conglomerate or lignite are present, however. Many of the light colored rocks are so thoroughly kaolinized that it can not be positively determined from microscopic study whether they are tuff or lava. Exposures in the Sunnyside mine show that some of this rock contains numerous irregular fragments of similar material. In and near this mine a nearly black rock, probably about 45 feet thick, over-

[7] Umpleby, J. B., and Livingston, D. C.: *op. cit.*, p. 6.

lies the beds of altered light colored rock which constitute the ore. The dark rock is composed of fragments of silicic lava of irregular size and shape, in a fine grained matrix, apparently composed of clastic grains of glass and lava. This rock is so thoroughly kaolinized that, when wet, it can be molded to some extent in the fingers. The contact with the light colored bed below is rolling. In places the dark upper rock fills crevices in the light one, which was evidently previously fractured. The filling of the crevices is so irregular as to suggest that it was done by solid fragments rolling over the ground as a volcanic mud flow rather than by fluid lava. The dark rock will consequently be referred to in this report as the mud flow. The light colored rock below is composed of a number of beds of only slightly differing character, aggregating several hundred feet in thickness, of which the mineralized rock in the mine workings makes up somewhat over 50 feet. Differences in color permitted distinction in underground mapping between light and dark phases of this rock, but no diagnostic differences between these varieties are perceptible under the microscope. In some places in the mine they grade into each other. Elsewhere the contacts between them are fairly sharp. Whatever the exact character and mutual relations of the two varieties, both, prior to alteration, consisted mainly of glass and a variable proportion of small quartz grains.

The strata on both flanks of the Thunder Mountain ridge are rolling and vary in attitude within short distances, in part because of irregularities in original deposition. In a general way the rocks are flexed into an anticline of northwesterly trend whose axis lies near the crest of the ridge. Dips on either flank rarely exceed 25° and much of the rock lies nearly horizontal. A few hundred feet east of the caved ground above the main Dewey workings there is a nearly vertical fault, which brings the basalt against the tuffaceous conglomerate. It strikes N. 50° W. (somewhat more northerly than the average attitude of the strata) and has a downthrow of roughly 200 feet to the southwest. The same or a related fault zone was followed by the now inaccessible workings

of the Dewey to a depth of about 240 feet. No faults of any magnitude exist in any of the underground workings accessible at the time of visit, although numerous slips resulting from minor adjustments are present.

ORE DEPOSITS.

Character of the Mineralization.

All the light cream to buff-colored strata in the district, both tuff and lava, are altered in a fashion which differs in degree rather than in kind from that which characterizes the developed ore deposits. It appears that tenuous solutions suffused these strata over a wide area and were locally concentrated where conditions were favorable. The more intensely mineralized material constituting the ore bodies can scarcely be distinguished from the surrounding rock except by assay.

The principal products of the mineralization, in so far as determined by the present study, are gold with its associated silver, pyrite, quartz, and clay minerals. It appears from the reports of those familiar with the Dewey mine that small amounts of other metallic minerals, supposedly including arsenides, existed there, especially in the deeper workings. Evidence exists that the percentage of recovery by amalgamation in ore from this mine decreased somewhat with depth. Other ore deposits in the Challis volcanics in the surrounding region are now known commonly to contain a selenide resembling naumannite, so fine-grained and sparsely disseminated as to be recognized only on the basis of chemical examination.[8] This mineral is consequently to be expected in some of the ore in the Thunder Mountain district and may account for some of the reported difficulties in recovering the gold from this ore.

Pyrite is the only sulphide that has been recognized, and this is nowhere abundant. Rarely there are nodules of pyrite containing leaf gold in the center. These nodules assay $40 to $80 a

[8] Ross, C. P.: Ore Deposits in Tertiary Lava in the Salmon River Mountains, Idaho. Idaho Bur. of Mines and Geology Pamphlet 25, pp. 13–16, 1927. Also subsequent unpublished data.

ton in gold.[9] The rest of the pyrite, commonly in tiny crystals, is presumably also auriferous, but a large proportion of the gold is in fine flakes of the native metal. Much of it appears to be deposited in cracks in the rock, rather than uniformly distributed through it. The highest annual average recovery in the Dewey mill during the period from 1902 to 1907 inclusive was 0.456 ozs. gold and 0.259 ozs. silver to the ton in 1904, and the lowest was 0.200 ozs. gold and 0.140 ozs. silver, in 1907. The weighted mean for this period was 0.2915 ozs. gold and 0.1884 ozs. silver to the ton. The loss in milling is unknown. It is reported that the ore mined ranged in value from $6 to $30 a ton, and the above figures indicate that its average value was somewhat over $8 a ton. Judging by the reported returns from the relatively small proportion of ore so far milled at the Sunnyside and from the results of the owners' sampling, the main ore body there is of similar average tenor. There are considerable masses in which the tenor is $5 a ton or less, and in the Burr Oak tunnel, over 200 feet below the haulage tunnel, values of $1 and somewhat more are reported. Less information is available regarding other mines in the district, but it appears that, outside of the Dewey and Sunnyside, no ore bodies of any magnitude averaging over $5 a ton are known.

The gangue in all the deposits consists of the rhyolitic country rock in which the original feldspar and glassy material have been kaolinized and locally somewhat silicified. In some places, particularly in the Sunnyside, there are irregular seams filled either with white clay or fine-grained quartz. The clay is clearly a fissure filling and similar in mode of origin to the quartz seams. Study by and under the direction of C. S. Ross, shows that the clay is made up of two slightly different potassic clay minerals resembling hydro-mica. Embedded in the clay are numerous small, doubly-terminated quartz crystals. The definitely crystalline character of the clay, distinctly different from ordinary gouge clay, is well shown in Fig. 2. The chemical character of the clay is indicated by the two following analyses, made on samples from the Sunnyside mine from which the quartz had been removed.

[9] Umpleby, J. B. and Livingston, D. C.: *Op. cit.*, p. 6.

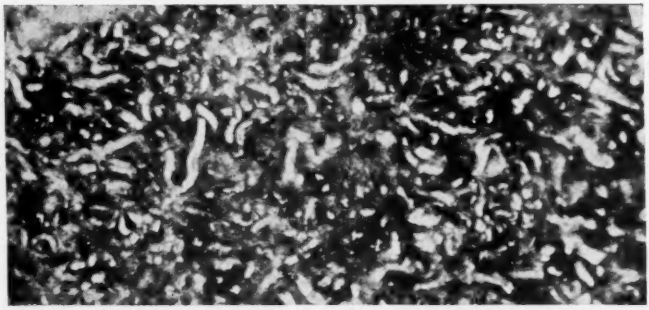

FIG. 2. Photomicrograph of clay from Sunnyside Mine. × 40. By C. S. Ross.

ANALYSES OF TWO SPECIMENS OF CLAY FROM SUNNYSIDE MINE.

Analyst J. G. Fairchild, U. S. Geol. Survey.

SiO_2	57.02	47.50	K_2O	5.45	7.90
Al_2O_3	26.10	31.52	H_2O	N.D	N.D
Fe_2O_3	0.92	1.18	H_2O	8.20	9.92
FeO	0.38	0.50	TiO_2	none	tr.
MgO	0.50	0.72			
CaO	tr.	0.64		99.57	100.26
Na_2O	none	0.19			

Structural Relations.

In the Dewey mine, so far as can be judged from available information and mine maps, the ore lay largely along a nearly vertical fracture zone. This evidently served as a conduit for the solutions but mineralization was by no means confined to the brecciated rock. For example, development on No. 1 level penetrated mineralized ground for a length of over 600 feet and a width of over 200 feet, although much of this was of a grade below that then being milled. In the extensive surface cuts, mineralization, at least in part hypogene, extends far into unbrecciated rock. This mine contained over 2000 feet of workings which extended through a vertical range of about 240 feet. Mineralization continues below this depth, but ore of satisfactory grade appears to have been scanty below a depth of 114 feet. Stoping was carried

through to the surface. In spite of the difficulty of maintaining openings in the clayey ground there was one stope 10 square sets high, several sets wide and 46 sets long, showing that the better ore in the fracture zone was in shoots of fair size.

Conditions in the Sunnyside mine are fundamentally different. At the time of visit, the main workings totalled about 3600 feet, but stopes were comparatively meager. Emphasis had been laid on development rather than production. The better ore is concentrated in irregular, ill-defined masses immediately below the volcanic mud flow, which although thoroughly kaolinized appears to contain little or no gold. Both laterally and in depth the limits of the ore are those imposed by decrease in assay value. Most of the rhyolitic rock throughout the workings appears to contain appreciable amounts of gold. There is a progressive decrease downward to the lowest development over 250 feet below the mud flow.

No fault or breccia zone of consequence is exposed in the workings, but in numerous places the rhyolitic rock is broken by slips and irregular seams, in part gouge-lined. The better defined slips strike north or a little east of north and dip steeply west. They appear to record merely minor movements of readjustment in the kaolinized rock.

The other accessible workings in the district, notably the Venable and Standard mines, expose diffused mineralization more closely resembling that at the Sunnyside than that in the fracture zone at the Dewey. Rock somewhat like the mud flow at the Sunnyside is present in some of the other workings but development is insufficient to show its relation to the ore.

Origin.

The relations outlined above suggest that mineralization was occasioned by tenuous solutions that suffused the strata sufficiently porous or easily replacable to permit penetration. Where conditions were favorable, concentration took place. The fault zone at the Dewey, which provided a relatively easy path for the solutions, and the impervious volcanic mud-flow at the Sunnyside, which trapped rising solutions each in different ways, brought

about such concentration. The diminution in metallization with depth, the structural relations and the character of the assemblage of minerals deposited, strongly indicate that mineralization was brought about by heated, probably alkaline, solutions, rather than by the cool acid solutions characteristic of supergene circulation. At first glance the abundance of clay minerals might suggest an alteration process similar to that of weathering, but the principal resemblance is in superficial appearance. Where the clay fills fissures, these pinch out upward rather than downward. The clay minerals are in clean-cut crystal flakes, which is not true of clays derived from weathering. They are rich in potash and contain almost no soda. According to C. S. Ross, in clay produced by weathering the reverse is generally true even though many of the rocks weathered contain abundant potash. The presence of quartz crystals in the clay seams and of fresh pyrite in the kaolinized rock also indicates that supergene processes have played little part in the formation of the ore containing them.

Obviously supergene processes have had some effect locally, as is evidenced by the presence near the surface of small amounts of " limonite " and manganese oxides. The ore originally mined by sluicing was more or less oxidized and probably was locally enriched by supergene processes. At one point on Dewey ground, direct proof of deposition of rich gold stringers by descending solutions was observed during the visit in 1926. Prospectors were working thin, nearly vertical seams in tuff beds containing gold in flakes and grains, much of which was readily visible to the unaided eye, far coarser than that characteristic of the ore at depth. So much of the gold was concentrated near the upper contact of an irregular lignitic bed as to indicate that it was precipitated from water descending in the seams by the carbonaceous matter in the lignitic bed. However, processes of this sort were effective for only a short distance below the surface.

The data summarized above imply that the dominant process of mineralization was diffusion of hypogene solutions and deposition from them. The source of these solutions is not quite so clear. It is possible that Miocene granite or related intrusive rocks are present at depth much closer to the Thunder Mountain

district than is evidenced by known exposures. If so, emanations from them may have caused the mineralization. Another possible source is in the volcanic strata themselves. Lava is not commonly thought of as giving off large quantities of aqueous emanations, yet there is abundant evidence that a certain amount of such material is present in many lavas. Hydrothermal alteration sufficient to decompose ferromagnesian minerals and sericitize feldspars is common. The filling of vesicles with such minerals as quartz and zeolites is generally considered to be occasioned in part at least by aqueous emanations from the cooling lava. It would require but little variation in composition and increase in volume for genetically similar solutions to produce results such as those observed in the ore deposits of the Thunder Mountain district. Such solutions might be derived in part from the very strata now containing the ore deposits, but probably came in large part from more or less similar underlying strata.

These ore deposits differ in numerous features from most of those elsewhere in Idaho. There are even marked differences between them and the more common deposits in Tertiary lava, characterized by ribbon-banded quartz, although, as has been pointed out,[10] there are also important resemblances. These differences point to some modification at least of the conditions governing the formation of the deposits. The theory that the mineralizing solutions of the Thunder Mountain district were derived from the same sources as the volcanic strata seems more probable than that they came from some granitic mass at depth.

A somewhat different theory has been advanced by Zies[11] to account for conditions in the Valley of Ten Thousand Smokes in Alaska, which are in some respects similar to those of the Thunder Mountain district. He considers that silver, lead, copper, tin, molybdenum and zinc found in fumarole deposits in the Valley of Ten Thousand Smokes were derived from the surrounding rhyolitic pumice and were concentrated by means of emanations of steam from some fairly deep-seated igneous body. Part of the

[10] Ross, C. P.: *Op. cit.*, pp. 14, 15.

[11] Zies, E. G.: The Concentration of Metallic Constituents by Volcanic Emanations. Bull. Nat. Research Council No. 61, pp. 263–265, 1927.

material deposited, notably the magnetite, he regards as having come from below in combination with halogens. Such a theory would accord with the conditions which appear to have existed during the formation of the ore bodies of the Thunder Mountain district, except that there is little indication of the existence of restricted fumarolic vents, and all available evidence suggests that the approximately contemporaneous granitic intrusions lie far east and northeast of this district.

Commercial Outlook.

The comparative neglect that the Thunder Mountain district has suffered since 1908 results in part from its remoteness and in part from lack of clear comprehension of its ore deposits, which differ in material respects from any others in Idaho. Recent developments to the west have greatly reduced the distance from modern roads, and the improvement in motor trucks and airplanes has made remoteness from railroads a much less serious factor than was formerly the case. Much more quantitative information as to grade and size of the ore bodies is required before an adequate concept of the commercial value of the deposits can be arrived at. The grade of the ore is not high, and difficulties in mining in the clayey ground and in recovering the fine and partially refractory gold are to be anticipated. However, modern technique should overcome these disadvantages, and it would seem that the outlook is sufficiently favorable to warrant thorough investigation in the near future by an organization capable of operating on a large scale.

The amount of mineralized rock present is very large. Pockets and stringers of high grade, mainly supergene, ore can still be found here and there by individual prospectors, but the quantity of such ore remaining is probably so small as to be negligible in plans for any large-scale operations in the district. A company reopening any of the mines must expect to handle ore containing $8 to the ton and less. The average tenor of the ore might well prove to be little more than half this figure and much of the mineralized material is of even lower grade. In many places ore will be found practically at the surface. Elsewhere the overburden

may be considerable. Although the ore shoots developed in the Dewey and Sunnyside mines decreased markedly in grade below a depth of 100 feet, there is no apparent reason why structural conditions favorable to the formation of other ore shoots should not exist at least to the bottom of the local light-colored rocks.

The most profitable period in the history of the district appears to have been that in which the Caswell brothers and Huntley operated by sluicing the rock at the surface. This process is of obviously limited application, but some such cheap, non-selective method of mining seems to offer the most hope for future development. Presumably at least 60 per cent. of the gold could be recovered by simple amalgamation. Flotation or other processes which could be utilized in a modern mill would doubtless result in a high recovery.

Although mineralization exactly like that at Thunder Mountain has not been discovered in amounts sufficient to be of commercial interest anywhere else in Idaho, there remains a possibility that prospecting directed specifically to that end might be rewarded. Outcrops of such lodes would be so inconspicuous and differ so much from the quartz ledges commonly sought that they might well escape notice. Mineralization is certainly widespread in the Challis volcanics. This is attested not only by the famous Yankee Fork district, Custer County, and the less known Parker Mountain and Gravel Range districts, Lemhi County, but by numerous scarcely prospected occurrences scattered over the Salmon River Mountains.[12] Most of the mineralization is in or closely associated with rhyolite and rhyolitic tuff in the upper part of the Challis volcanics. This horizon is easily recognized, since it everywhere consists largely or entirely of nearly white rocks. Any area in it where there has been intense kaolinization or the dissemination of pyrite or quartz is worthy of investigation.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

[12] Ross, C. P.: *Op. cit.*, pp. 1–21, also subsequent unpublished observations.

INFLUENCE OF BASIN RANGE FAULTING IN MINES AT BINGHAM, UTAH.

ROLLIN FARMIN.

INTRODUCTION.

THE Oquirrh Range, Utah, is the most easterly of those northerly trending fault-block mountain units that traverse the Great Basin, and are characterized by what Gilbert [1] has termed Basin-Range structure. This range is about 30 miles long and 5 to 15 miles wide, and its north end terminates against Great Salt Lake. The important mining camp of Bingham is situated in the north-central part of the range and the camps of Stockton, Ophir, Mercur and Sunshine are successively farther southward. And, in southerly continuation of the Oquirrh, the East Tintic Range contains the rich Tintic mining district. Basin-Range faulting along portions of the Oquirrh West Front was early recognized [2] and faults of this type have recently been described along much of the southern half of the range, where Gilluly [3] found that certain of them have been mineralized.

In the Bingham mining district the locally well-known Occidental fault is an important geologic factor in the Highland Boy mine (production $87,731,000) and in adjoining mines. Because this fault now appears to be a Basin-Range structure, its control of mineralization and its relation to the other geologic features at Bingham deserve special mention. Some of its characteristics may be expected in other of the many Basin-Range faults in the region.

[1] Gilbert, G. K.: Studies of Basin-Range Structure. U. S. Geol. Surv. Prof. Paper 153, p. 1, 1928.

[2] Gilbert, G. K.: Lake Bonneville. U. S. Geol. Surv. Mon. 1, p. 352, 1880.

[3] Gilluly, James: Basin Range Faulting along the Oquirrh Range, Utah. Bull. Geol. Soc. Amer., vol. 39, pp. 1103–1130, 1928.

OCCIDENTAL FAULT, A BASIN RANGE-STRUCTURE.

Underground Exposures.—The Occidental fault lies at the southwestern end of the Bingham mining district (Fig. 1), where underground workings in the Utah-Delaware mine (formerly Utah Consolidated, Highland Boy and Yampa mines) and in the Utah Metal and Tunnel mine have developed it intermittantly for 3500 feet along its strike and 2150 feet down the dip. Such abundant exposures of the fault zone permit a more intimate examination of its features than is possible in the usual

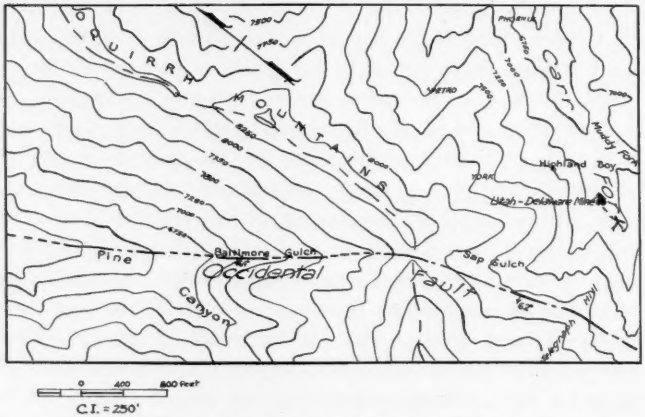

FIG. 1. Southwestern portion of Bingham district, Utah, showing outcrop of Occidental fault. (Topog. after U. S. Geol. Survey.)

Basin-Range fault occurrence, where surface expression alone may be seen.

Underground exposures of the fault zone commonly consist of 5 to 10 feet of intimately ground friction-breccia containing two or more slickensided walls. At exceptional points the rock has been crushed as far as 100 feet beyond the main fault walls, and the zone is a wet, sandy ground that is difficult to crosscut. Limestone breccia in the zone is mostly altered to a rubbery gouge, whereas the more abundant quartzite breccia varies from a sandy mass, kept granular by recent strains, to a hard rock of well cemented breccia at points undisturbed by recent movements.

The average strike of the fault plane is N. 25° W. and the dip 62° SW. Although there are local variations as large as 20° from the general attitude, the fault plane is exceptionally regular and its position may be projected from level to level of the mines with confidence.

Groovings which would indicate the direction of relative movement are lacking. The small striae on slickensided walls only indicate the direction of recent movements along the fault zone, with which the direction of the earlier major movement may not agree.

Displacement.—On each side of the Occidental fault, distinctive limestone members of the Bingham Quartzite dip northerly 30° to 60°, and from their displacement the fault movement can be estimated. Beds on the hanging-wall (west) side are relatively downthrown 1500 feet; or they have an apparent horizontal offset of 2500 feet southward. Because it has not been possible to match actual points in beds on opposite sides of the fault, such as displaced halves of a transected fold, the total displacement of the fault is not known. If the direction of movement were nearly parallel to the dip of the beds, the total displacement would be much larger than the above simple vertical or horizontal displacements. The fault is more probably a rotational one because its movement appears to increase to the north but probably splits up and dies out to the south.

Topographic Expression.—The surface trace of the fault is exposed in short prospect tunnels and trenches adjacent to the productive area of the mines. It extends northward through the saddle in Telegraph Hill,[4] across the eastern slope of Clipper Peak, and enters the sharp saddle in the main Oquirrh ridge at the head of Sap Gulch on the Bingham side, and at the head of Baltimore Gulch on the west side (Fig. 1). Northward, beyond the saddle, the fault trends down the sharp channel of Baltimore Gulch, along the east side of Pine Canyon and along the bases of the steep, triangular-faceted spurs of the Oquirrh West Front. Deep mine workings have developed the fault beneath Baltimore

[4] Hunt, R. N.: The Ores in the Limestone at Bingham, Utah. Trans. Amer. Inst. Min. Eng., 70, p. 861, fig. 3, 1924.

Gulch, making certain its identity with the Basin-Range fault on the surface. A good outcrop of the fault occurs at a waterfall in the lower end of Baltimore Gulch, where it consists of a central zone of cemented fault breccia and rock flour, bounded by parallel slickensided walls four feet apart, with irregularly shattered and brecciated rock extending 20 to 75 feet on either side.

On the surface, above the point in the mine where the fault has a 1500-foot throw, the topographic relief produced by the fault is noticeable but not large. North of Pine Canyon, however, the topographic relief due to the fault increases to 2500 feet, and presumably the stratigraphic displacement is even greater. In its non-persistence the Occidental fault resembles a Basin-Range fault [5] twelve miles southward, which dies out completely two miles south from a point where the stratigraphic displacement is 3000 feet.

RELATION OF OCCIDENTAL FAULT TO MINERALIZATION AND TO OTHER GEOLOGIC FEATURES.

The ores at Bingham [6] are of three types: (*a*) bodies of various combinations of copper, lead, zinc, silver and gold minerals replacing siliceous limestone members of the Carboniferous Bingham Quartzite formation, (*b*) disseminated "porphyry copper" ore, and (*c*) fissure ores in monzonite intrusive rock. The sequence of geologic events climaxed by mineralization is: (1) early normal faulting of the sedimentary rocks; (2) folding, which produced some large bedding faults; (3) Basin-Range faulting and northeast faulting; (4) intrusion of monzonite and accompanying metamorphism of the sedimentary rocks; (5) additional northeast faulting, following by hydrothermal alteration and by mineralization; and (6) additional small movements on all faults, resulting from renewed movement on Basin-Range faults.

[5] Gilluly, James: Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah. U. S. Geol. Surv. Prof. Paper 173, pp. 83–85, 1932.

[6] Boutwell, J. M.: Economic Geology of the Bingham Mining District, Utah. U. S. Geol. Surv. Prof. Paper 38, p. 123 et seq., 1905.

To support the above stated sequence: (1) early normal faulting is represented in Utah-Delaware and Utah Metal mines by South and Top faults (Fig. 2) which offset the limestone beds as much as 900 feet. Subsequent folding, faulting, intrusion, alteration, and mineralization have greatly obscured these ancient faults. (2) Yampa Foot Wall fault is an example of a strong bedding slip produced along a sharp stratigraphic contact by folding strain. It displaces South fault 450 to 550 feet and cuts the quartzite beds which South fault left aligned with the

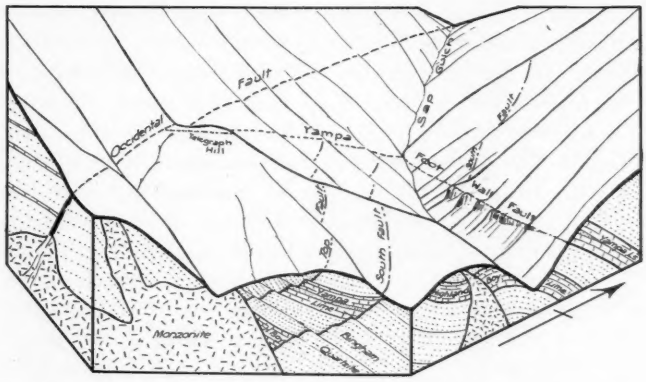

FIG. 2. Diagram of surface and underground geology near Utah-Delaware mine, Bingham, Utah.

base of the Yampa limestone (Fig. 2). (3) Both Basin-Range faulting (Occidental) and northeast faulting (*e.g.* Ball fault) truncate folds and cut bedding slips; therefore they are younger than folding. Also, lack of drag along the Occidental fault argues against its origin as a rupture during folding strain. (4) Intrusion of the monzonite followed Basin-Range faulting—perhaps closely—because it sent dikes along the Occidental and Ball faults. Moreover, the Last Chance monzonite stock stoped out the Occidental fault zone, although later minor fractures have extended into the monzonite in rough prolongation of the fault zone. The intrusive is likewise younger than folding, as

has been suggested by Hunt,[7] because dikes and sills cut cleanly through folded limestone beds without disturbing the symmetry of the separated limbs of the folds (Fig. 2). (5) Postmineral movements on northeast faults have produced slickensides in ore and have offset sills of monzonite a few tens of feet. Recent Basin-Range movement on the Occidental fault probably is not much greater than 100 feet at the southern end but may be considerably greater northward along the fault. A common origin for all recent movements on the various faults seems likely.

Ore deposition in the limestone has been controlled at different points by a variety of structures, both tangible and obscure. Prominent among them are plunging intersections of beds or bedding slips against northeast faults, and roof structures, such as the intersection of Yampa Foot Wall fault against the South fault, together with a northeast fault to close the structure. Although the Occidental fault zone has been sparingly mineralized at points, it has played a much more important part as a roof structure, presenting a relatively non-replaceable overhanging wall of quartzite to mineralizing solutions that raked up toward it through the limestone. For this reason a number of ore bodies increase in size as they approach the fault and either mushroom out against it or are deflected along it. A Basin-Range fault has thus formed a definite, favorable boundary for several important ore bodies at Bingham.

EUREKA, UTAH.

[7] Hunt, R. N.: *Op. cit.*, pp. 863–866.

DISCUSSION AND COMMUNICATIONS

DISSEMINATED GALENA, UPPER CAMBRIAN OF CENTRAL MINERAL REGION, TEXAS.

Sir:—Mr. Baker,[1] in describing the disseminated galena in the Cap Mountain limestone (Upper Cambrian) of the Central Mineral Region of Texas and surmising as to its origin, has overlooked a possibility that may appeal to some as a more probable interpretation of its origin. To the writer, an epigenetic origin for the galena (and other sulfides) seems more feasible than the suggestions made by Mr. Baker. Mr. Baker states (p. 164) that as far as he "has been able to determine, the galena of central Texas is syngenetic, having been deposited with the limestone and glauconite in the Upper Cambrian sea." This statement shows that he has ruled out at once a possible epigenetic source. Yet, he mentions two occurrences of galena, one along a stylolitic seam and another in a small cavity, that are certainly epigenetic. The geologic factors he describes are favorable to an epigenetic origin; *i.e.*, the occurrence of the galena in a limestone overlying a sandstone and with a formation not far above that contained shale. Furthermore, the limestone is near the margins of pre-Cambrian crystallines. Faults of mid-Pennsylvanian age, having a maximum displacement of 1,800 feet, occur in the area. These faults may or may not be related to the mineralization, which may have occurred long before. However, it is probable that faults cutting the pre-Cambrian beds were in existence before the Upper Cambrian beds were deposited (these faults probably determined the position of the later faults) and may very well have been the openings along which solutions from below worked their way outward. These considerations, together with the fact of the inadequacy of our criteria for determining the syngenetic or epigenetic origin of sulfides in sediments, certainly makes feasible the suggestion of an epigenetic origin, which might very well be magmatic.

W. A. Tarr.

University of Missouri,
Columbia, Missouri.

1 Baker, C. L.: Econ. Geol., vol. 28, pp. 163–170, 1933.

REVIEWS

Prospector's Field-Book and Guide in the Search for and Easy Determination of Ores and Other Useful Minerals. By H. S. OSBORN. 9th Ed. Revised and enlarged by M. W. von Bernewitz. Pp. xiii + 364, figs. 57. Henry Carey Baird and Co., N. Y., 1928. Price, $3.00.

This little book is not intended to guide the prospector in the search for ores, but rather to familiarize him with the conditions under which the different ore minerals should be found and to enable him to recognize them when found. The author well states in his introduction that "many valuable deposits have been overlooked or abandoned [by the prospector] due to a lack of knowledge of mineralogy and mining." He therefore offers him a simple little treatise which contains elementary descriptions of minerals and rocks, simple directions for surveying areas, and methods for the detection of the significant constituents of ore minerals. The greater part of the book describes the various ore-minerals, gem stones and other non-metallic minerals of economic value, outlines tests for most of the ore minerals, mentions their methods of occurrence, describes the nature of the ore of which they form the important part and gives a few notes on the geology of some of the mining areas producing them. The portion devoted to the non-metallic minerals is the less satisfactory part of the volume. It merely describes the minerals and gives a few tests for some of them. In several places it is incomplete and in others is vague or inaccurate. It makes no reference to pentlandite as an ore of nickel, nor of ilmenite as a source of titanium. It does not include Georgia as one of the States in which barite is mined, and declares that Quebec produces most of the world's mica, whereas, he states, the United States has a number of deposits, but they are not of great importance.

In spite of its weaknesses the book contains a lot of information valuable to the prospector, mainly in enabling him to recognize many substances with which he is not already familiar.

W. S. BAYLEY.

A Manual of Foraminifera. By J. J. GALLOWAY. Pp. 483, pls. 42. Principia Press, Bloomington, Ind., 1933.

This book presents a more complete classification of the foraminifera than has hitherto been available.

The work is largely a study of the phylogeny of the families, subfamilies, and genera of foraminifera, but the treatment of the families and genera differs from that of previous authors principally in the more precise use of the rules of biologic nomenclature; in the application of the laws of evolution to determine classification; in the greater completeness of definitions, synonymy, and references; and in the recognition of the importance of the geologic record in interpreting phylogeny. A chart showing the development of the thirty-five families is given, followed by companion charts showing the evolution of the genera within the families.

This work marks an important advancement in the science and there is no doubt that it will greatly simplify and clarify the subject for micropaleontologists. GLADYS D. BILLINGS.

Atoms and Cosmos. By HANS REICHENBACH. Translated and revised by E. S. Allen. Pp. 300, figs. 19. Macmillan Co., New York, 1933. Price, $2.00.

An account of modern physics, based on a series of broadcasts in Berlin in 1930, therefore without presupposition of a knowledge of physics or astronomy. It deals with space, time, motion, light, matter, the atom, and philosophical consequences. It is written by an authority, in a manner suited for the non-specialist, to show the interrelationship between philosophy and natural science and to unite the physical theories of today in a picture of the world. Scientists and laymen alike will profit from it and enjoy it.

Ores and Industry in the Far East. By H. FOSTER BAIN. 2nd ed. revised. Pp. 288, figs. 31. Council on Foreign Relations, 45 East 65th St., New York, 1933. Price, $3.00.

The first edition of this valuable book has already been reviewed in this Journal. In the second edition considerable revision and additions are noted. New data are included regarding Manchuria and Jehol that throw light on the recent events in that region. The new edition is timely and should be of great value to all who are interested in the Far East.

New College Geography. By R. PEATTIE. Pp. 583, figs. 189. Ginn & Co., New York, 1933. Price, $3.00.

This is a text book for college purposes that deals with the principles of geography rather than with regional descriptions. The subjects treated are the atmosphere, climates, and weather; the physical characters and the relation of man and commerce to jungles, deserts, forests, mountains, and islands; agricultural areas; rivers and valleys; the seas and ships; mineral resources and water power.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

BOOKS RECEIVED.

By

DAVID GALLAGHER.

Geology of the Robertson, Humdinger, and Robert E. Gold Mines, Southwestern Oregon. By P. J. Shenon. Pp. 22, pls. 8, figs. 1. Notes on the Chieftain and Continental Mines, Douglas County, Oregon. By F. G. Wells. Pp. 6, pls. 2, figs. 1. U. S. Geol. Surv. Bull., 830–B. Washington, 1933. Price, 15 cts.

Geology of the Boston Area, Massachusetts. By L. La Forge. Pp. 105, pls. 15, figs. 6. U. S. Geol. Surv. Bull. 839. Washington, 1932. Price, 40 cts. Physiography, stratigraphy, structure, and geologic history, geologic maps in color, scale 1 : 62500.

Lead. 2d Ed. Mineral Industry of the British Empire and Foreign Countries. Pp. 253. Imperial Institute, London, 1933. Price 4s plus postage. Scientific, industrial, and economic enucleation, and summary of world occurrence and production.

Mineral Investigations in the Alaska Railroad Belt, 1931. By S. R. Capps. Pp. 16, pls. 1. U. S. Geol. Surv. Bull. 844–B. Washington, 1933. Price, 5 cts.

Geology and Mineral Resources of the Middletown Quadrangle, Pennsylvania. By G. W. Stose and A. I. Jonas. Pp. 86, pls. 15, figs. 16. U. S. Geol. Surv. Bull. 840. Washington, 1933. Price, 40 cts. Stratigraphy, structure, geologic history, and mineral resources (nonmetallics). Geologic map in color, scale 1 : 62500.

Mineral Industry of Alaska in 1931 and Administrative Report. By P. S. Smith. Pp. 132, figs, 3. U. S. Geol. Surv. Bull. 844–A. Washington, 1933. Price, 10 cts. Production statistics, and bibliography of Alaska geology.

Contribution à l'Etude Géologique du Bassin Charbonnier de la Lukuga. By A. Jamotte. Pp. 75, pls. 8. Le Conglomérat de Base de la Série de Roan dans la Région Sud-Est du Katanga. By A. Jamotte and P. Van den Brande. Pp. 3, figs. 3. Annales du Service des Mines, Tome II–1931, Comité Spécial du Katanga. Bruxelles, 1932.

Proceedings, First Meeting of African Geological Surveys, South Equatorial Section, 1931. (Sub-commission of the International Geological Congress.) Pp. 31. Louvain, 1932. Representatives of the geological organizations of these countries met, discussed, and agreed upon vital questions of nomenclature and correlation. The benefits of this procedure are obvious, and such timely, frank, and effectual coöperation deserves the hearty approbation of all geologists. A fine geologic map in color is included, covering all of Central Africa from coast to coast; scale 1 : 5,000,000.

Production and Value of Minerals and Mineral Products in Michigan,

1927 to 1931 and Prior Years. By W. OSGOOD AND O. F. POINDEXTER. Pp. 46. Michigan Geol. Surv. Summary Report No. 1, 1933.

Kyanite in Virginia. By A. J. JONAS AND J. H. WATKINS. Pp. 52, pls. 11, figs. 2. Virginia Geol. Surv. Bull. 38. University, Va., 1932. Description of the geology of a belt of kyanite-bearing quartzites and pegmatites. Geologic map of Central Virginia in color, scale 1:125,000.

Canadian Limestone for Building Purposes. By M. F. GOUDGE. Pp. 196, tables 6, pls. 40, figs. 11. Canada Mines Branch, No. 733. Ottawa, 1933. Price, 30 cts. General, history and statistics, Canadian resources and quarries (descriptions), prospecting and development, quarry practice, stone dressing, durability of limestone.

Canada Geol. Survey, Summary Report, 1932, Part A–I, No. 2331. Pp. 151. Ottawa, 1933. Placer and Vein Gold Deposits of Barkerville, Cariboo District, B. C., by W. A. JOHNSTON AND W. L. UGLOW; Geology and Placer Deposits of Quesnel Forks Area, Cariboo District, B. C., by W. E. COCKFIELD AND J. F. WALKER.

Canada Geol. Survey, Summary Report, 1932, Part A–II, No. 2333. Pp. 197, pls. 4, figs. 16, map. Ottawa, 1933. Mining Industry of Yukon, 1932, by H. S. BOSTOCK; Whitewater Gold Belt, Taku River District, B. C., by F. A. KERR; Zeballos River Area, Vancouver Island, B. C., by H. C. GUNNING; Vanadium-bearing Rock on Quadra Island, B. C., by H. V. ELLSWORTH AND H. C. GUNNING; Cadwallader Creek Gold Mining Area, Bridge River District, B. C., by W. E. COCKFIELD AND J. F. WALKER; An Occurrence of Magnesite near Clinton, B. C., by W. E. COCKFIELD AND J. F. WALKER; Some Mineral Occurrences in the Vicinity of Cranbrook, B. C., by C. E. CAIRNES; Brisco-Dogtooth Map-Area, B. C., by C. S. EVANS; Borings for Water, Oil and Gas in B. C., by W. A. JOHNSTON; Other Field Work.

Canada Geol. Survey, Summary Report, 1932, Part B, No. 2329. Pp. 107, pls. 3, figs. 14. Ottawa, 1933. Waterton Lakes-Flathead Area, Alberta and B. C., by G. S. HUME; Geology and Coal Deposits of Crowsnest Pass Area, Alberta, by B. R. MACKAY; Birch Ridge Structure, Alberta, by G. S. HUME; Artesian Water Areas of the West Half of Rush Lake and the East Half of Elbow Quadrangles, Southern Saskatchewan, by D. C. MADDOX; Deep Borings in the Prairie Provinces, by W. A. JOHNSTON; Other Field Work.

Canada Geol. Survey, Summary Report, 1932, Part C, No. 2332. Pp. 127, pls. 4, figs. 11. Ottawa, 1933. Great Bear Lake Area, Northwest Territories, by D. F. KIDD; Great Slave Lake-Coppermine River Area, Northwest Territories, by C. H. STOCKWELL; Maguse River and Part of Ferguson River Basin, Northwest Territories, by L. J. WEEKS; Amisk Lake Area, Saskatchewan, by J. F. WRIGHT; Other Field Work.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SCIENTIFIC NOTES AND NEWS

C. K. Leith is serving as chairman of the subcommittee on Mineral Services and Publication Policy of the Business Advisory and Planning Council for the Department of Commerce.

N. H. Darton, of the U. S. Geological Survey, and others, whose retirement under the recent economy act was announced last July, have since been reinstated in their former positions.

Richard Stappenbeck, of the Department of Geology, University of Berlin, has been awarded the Silver Nachtigall medal of the Geological Society of Berlin. Dr. Stappenbeck is now studying oil possibilities in Mendoza province, Argentina.

P. R. Bradley succeeds his brother, the late F. W. Bradley, in the presidency of the Alaska Juneau Gold Mining Company.

N. W. Hayward, of El Paso, Texas, was a recent visitor in New Haven on his return from a trip to Cuba.

Harry Townsend, of Seattle, Wash., is engaged in a development program for the Alaska Ketchikan Gold Mining Company on Thorne Arm, Alaska.

C. K. Leith, of the University of Wisconsin; W. C. Teagle, president of the Standard Oil Company of New Jersey; and E. T. Stannard, president of Kennecott Copper Corporation, are included in a committee of 41 appointed to assist in administration of the Industrial Recovery Act.

The next annual meeting of the Geological Society of America will be held in Chicago, December 28–30. The Society of Economic Geologists will hold its annual meeting in conjunction with that of the Geological Society.

The Sixteenth International Geological Congress had a registration of about 750. This was larger than had been expected in view of the present economic conditions. The excursions had a smaller attendance than anticipated, but were highly spoken of, in particular Excursion A–2, under the guidance of J. T. Singewald, which included the mining areas of the East and was admirably arranged and conducted. It afforded many interesting problems in economic geology. The transcontinental excursions were well patronized, but the number being below the required limit, special cars instead of special trains were used. The technical sessions of the Congress were well filled with excellent papers. The Washington group of geologists deserve great credit for the well planned and executed program.

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